Federal Multiagency Collaboration on Unconventional Oil and Gas Research

A Multi-Year Framework for Collaborative Research and Development

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Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

ACES	A Community of Ecosystem Services
AEO	Annual Energy Outlook
API	American Petroleum Institute
ATSDR	Agency for Toxic Substances and Disease registry
bbl	Barrel
bcfg	Billion cubic feet gas
BLM	Bureau of Land Management
BOEM	Bureau of Ocean Energy Management
BOR	Bureau of Reclamation
BMP	Best management practices
Bpd	Barrels per day
Br-DBP	Bromine Disinfection By-Product
BTEX	Benzene, toluene, ethylbenzene, and xylenes
Btu	British thermal unit
C	Carbon
CEA	Comprehensive Environmental Assessment
CDC	Centers for Disease Control
cf	Cubic feet
cfy	Cubic feet per year
CFM	Cubic feet per minute
CGF	Coso Geothermal Field
CH_3OH	Methanol
CH_4	Methane
CISN	California Integrated Seismic Network
cm	Centimeter
CMAQ	Community Multiscale Air Quality
CO	Carbon monoxide
CO_2	Carbon dioxide
CVO	Cascades Volcano Observatory
DOE	Department of Energy
DOI	Department of the Interior
DNA	Deoxyribonucleic acid
E&P	Exploration and production
EDX	Energy Data Exchange
EGS	Enhanced Geothermal Systems
EIA	Energy Information Administration
EHS	Environmental health and safety
EJ	Environmental justice
EPA	Environmental Protection Agency
EROS	Earth Resources Observation and Science Center
ERR	Economically recoverable resources
EUR	Estimated ultimate recovery
FE	Fossil energy
ft	Foot, Feet
FTIR	Fourier transform infrared
FWLA	Fugro William Lettis & Associates
gal	Gallon
GAO	General Accountability Office
GHG	Greenhouse gas
GIS	Geographic information system??
GRI	Gas Research Institute
h, hr	Hour
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulfide
HAP	Hazardous air pollutant
HCl	Hydrochloric acid
HERO	Health and Environmental Research Online
HF	Hydraulic fracturing
HHRA	Human Health Risk Assessment
HHS	U.S. Departnment of Health and Human Services
HIA	Health Impact Assessment
HTSV	High Throughput Screening Value
IS	Induced Seismicity
Gal	Gallon
GAM	Geographic analysis and monitoring
GPS	Global positioning system
km	Kilometer
kPa	Kilopascal
lb	Pound
LBL	Lawrence Berkeley Laboratory
lb/MMBtu	Pounds per million British

	thermal units
LCSN	Lamont-Doherty Cooperative Seismographic Network
LRS	Land remote sensing
m	Meter
MeOH	Methanol
Mg/L	Milligrams per liter
M	Thousand
Mbbl	Thousand barrels
Mcf	Thousand cubic feet
MM	Million
MMbtu	Million Btus
MMcf	Million cubic feet
MMcfy	Million cubic feet per year
MMgal	Million gallons
MOU	Memorandum of understanding
MPa	Megapascal
MSA	Multipollutant Science Assessment
NO_x	Nitrous oxide
N/A	Not applicable
NAS	National Academy of Sciences
NAAQS	National Ambient Air Quality Standards
NCEH	National Center for Environmental Health
NCCWSC	National Climate Change and Wildlife Science Center
NETL	National Energy Technology Laboratory
NetRA	Net resources assessment
NG	Natural gas
NIEHS	National Institute of Environmental Health Sciences
NIOSH	National Institute for Occupational Safety and Health
NNI	National Nanotechnology Initiative
NORM	Naturally occurring radioactive materials
NRC	National Research Council
NSPS	New source performance standard
NOx	Oxides of nitrogen
NWIS	National water information system
O_2	Oxygen
OCS	Outer continental shelf
ODNR	Ohio Department of Natural Resources
OSTP	Office of Science and Technology Policy
PAHS	Polycyclic aromatic hydrocarbons
PM	Particulate matter
pm	Parts per million
PNSN	Pacific Northwest Seismic Network
PPP	Public-Private Partnership
PSHA	Probabilistic Seismic Hazard and Risk Assessment
psi	Pounds per square inch
QSAR	Quantitative structure activity relationship
R&D	Research and development
RDBMS	Relational Database Management System
RUA	Regional University Alliance
SEAB	Secretary of Energy Advisory Board
SMCL	Secondary Maximum Contaminant Level
SO_2	Sulfur dioxide
SOx	Oxides of sulfur
SPE	Society of Petroleum Engineers
st	Short ton
STAR	Science to Achieve Results
STB	Standard barrel
STORET	Storage and retrieval
T&E	Threatened and Endangered Species
TCF	Trillion cubic feet
TDS	Total dissolved salts
tonne	Metric ton (1,000 kg)
TRR	Technically recoverable resources
TRV	Toxicity reference value
TSA	Technology Sustainability Assessment
UIC	Underground Injection Control
UOG	Unconventional oil and gas
U.S.	United States
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VOC	Volatile organic compound
WVU	West Virginia University
°C	Degrees Celsius

Letter to the Public

America's abundant unconventional oil and natural gas (UOG) resources are critical components of our nation's energy portfolio. UOG development can enhance America's energy security and create significant income, employment and other economic benefits which are crucial to the United States (U.S.) economy. For example, in 2011, the country's abundant domestic supplies of natural gas provided 25 percent of the energy consumed in the United States. Safe, responsible, and efficient development of unconventional domestic natural gas resources can play an important role in our energy future.

Nurturing these benefits is a central aim of the President's "Blueprint for a Secure Energy Future" of 2011 (Blueprint, 2011) and by the Secretary of Energy Advisory Board Subcommittee on Natural Gas of 2011(SEAB, 2011). The Research Framework (Framework) presented in this document outlines a multi-federal agency strategy to inform sound decisions at federal, state, tribal, and local levels, regarding the development of UOG resources. The document focuses on delineating a nationwide research strategy that is characterized by federal safety and environmental UOG research needs highlighted in the President's and the Secretary' directives.

In April 2012, the President issued an Executive Order which established a Multiagency Working Group to Support Safe and Responsible Development of Unconventional Domestic Natural Gas Resources (Working Group) (Executive Order, 2012). Consisting of a number of executive departments and agencies that have expertise in various aspects of unconventional natural gas occurrence and development, this Working Group will help assure the public that the best available science is guiding safe and environmentally sound practices regarding natural gas development.

Also in April 2012, the Department of Energy, Department of the Interior, and Environmental Protection Agency formed a formal partnership directed toward a focused, collaborative federal effort to address the highest priority challenges associated with safe and prudent development of unconventional shale gas, tight gas, shale oil, and tight oil resources (Multiagency, 2012). Subsequently, the federal agencies designated the Steering Committee representatives, with two members serving from each of the agencies, and one member from the White House Office of Science and Technology Policy. (Jackson, 2012)

This draft multi-year Research Framework is a result of that partnership, and is being made available for public review and comment. This Framework:

- Analyzes and synthesizes the state of knowledge of research on UOG resources–which are limited to shale gas, tight gas, shale oil, and tight oil for the purpose of this Framework–to assist in identifying and prioritizing additional research needs and new research directions;
- Identifies and categorizes research needs relevant to the safety and environmental sustainability of unconventional oil and natural gas exploration and production;
- Identifies gaps in available data and appropriate activities to address those gaps;
- Describes steps to promote transparency and maximize stakeholder participation and

notification;

- Establishes mechanisms for enhanced cooperative relationships among the three member agencies in planning and conducting research and reviewing the results; and
- Recommends future plans, goals, and objectives.

Please visit the Multiagency Collaboration on Unconventional Oil and Gas Research web page to find out more about this effort, or to provide your comments on this Research Framework: http://unconventional.energy.gov/index.html#. If you need additional information, please contact the partnership's Steering Committee at unconventional@hq.doe.gov.

Signed,

Steering Committee Members

Executive Summary

Background

Unconventional oil and gas (UOG), which includes oil and natural gas contained in shale or other "tight" geological formations, represents a significant domestic energy resource. Because of the very low permeability of these tight reservoirs, extracting oil and gas from them requires unconventional development and production methods.

In recent years, rapid developments in unconventional resource production technology have greatly expanded the volume of natural gas and oil that can be economically produced. Hydraulic fracturing—a process whereby producers pump specially engineered fluids containing sand into a reservoir at a high pressure and rate that unlocks the formation and increases its permeability by creating fractures or channels held open by sand grains through which hydrocarbons can travel—is one such technique that has evolved to the point where it has become economically viable over a much wider range of domestic resource opportunities. Hydraulic fracturing has been employed for decades, but today it is being widely used to produce oil and gas from underground formations that only a decade ago were considered to be non-commercial.

The emergence of shale gas as a major domestic resource is widely considered to be the most significant development in the U.S. energy sector in generations. Shale gas resources have become an important part of our domestic energy portfolio. Projections contained in the Energy Information Administration's (EIA) 2012 Annual Energy Outlook suggest that shale gas will approach one half of total U.S. natural gas production by 2035 (EIA, 2012). This development brings with it a host of significant benefits: job creation, reduction in energy imports, natural gas exports, reduction in greenhouse gas emissions, and the creation of new energy options for American businesses and families.

Like all resource extraction processes, hydraulic fracturing is accompanied by concerns over potential environmental impacts, and they might affect the UOG resources' ability to support national energy and environmental objectives. These concerns include potential impacts to water quality and availability, air quality, life cycle greenhouse emissions, ecosystem integrity, human health, community well-being, and the prospect of inducing seismic events (earthquakes). These potential impacts vary locally and regionally. Part of this variation stems from the specific geologic characteristics of the areas containing these energy resources, which can impact the timing of when resources are produced and the nature of potential impacts resulting from development and production (including the size of the footprint of the surface activities, the types and magnitudes of potential emissions, and the development methodology).

The Steering Committee will collaborate with a diverse set of stakeholders across the life cycle of UOG development and production and will actively seek out outreach opportunities as research plans are developed to address the range of topical areas. Key stakeholders that are expected include: the public; regulators and permitting entities; public health, occupational safety, and health agencies; UOG operators and employees; and researchers who depend on reliable information to predict effects of UOG activities.

The Federal Government's Role

In meeting the challenge of prudently maximizing the value of our nation's domestic oil and gas resources, a primary research role of the federal government is to comprehensively understand the concerns of the public, ensure that risks associated with these concerns are appropriately and scientifically quantified, and demonstrate that they are mitigated through the regulatory process at the local, state, or federal level. In the event that the private sector cannot or will not participate in the development of innovative new energy technologies, the government will play a role in the development of these critical technologies which serve the public interest.

As the stewards of millions of acres of public lands, the federal government also has the responsibility of working with the States to ensure that these lands are protected from potential environmental effects associated with UOG activities. In addition, the federal government works to ensure that consistent peer reviewed standards and protocols are followed in the sampling and analysis of water and biological resources.

Accomplishing these tasks requires a coordinated, cross-cutting research and technology development agenda. The scope of essential research is broad, and calls for integration and coordination across a wide range of stakeholders including researchers, industry, policy makers, regulatory agencies, and the general public.

The existing federal UOG research portfolio spans multiple agencies, reflecting the broad capabilities of these agencies. The President's Executive Order for "Supporting Safe and Responsible Development of Unconventional Domestic Natural Gas Resources," will ensure coordination of these activities throughout the federal government by charging federal agencies to pursue multidisciplinary, coordinated research on the safety and environmental sustainability of UOG activities (Executive Order, 2012).

Working Together

The Department of Energy (DOE), Department of the Interior (DOI), and Environmental Protection Agency (EPA) have the majority of federal research experience and expertise relative to the development of UOG resources (hereinafter referred to as the Agencies).

Each of these Agencies has a unique set of capabilities and experience. In order to achieve the goals of multiagency collaboration outlined in this document, each agency will:

1. <u>Focus on its area of core competency</u>. Each agency has a different combination of experiences, research strengths, personnel, resources and mission mandates, leading to complementary research core competencies (see **Error! Reference source not found.**Figure 1).
2. <u>Collaborate on research topics, as appropriate</u>. While each agency will focus on its area(s) of core research competency, there will likely be tasks for which the combined capabilities of more than

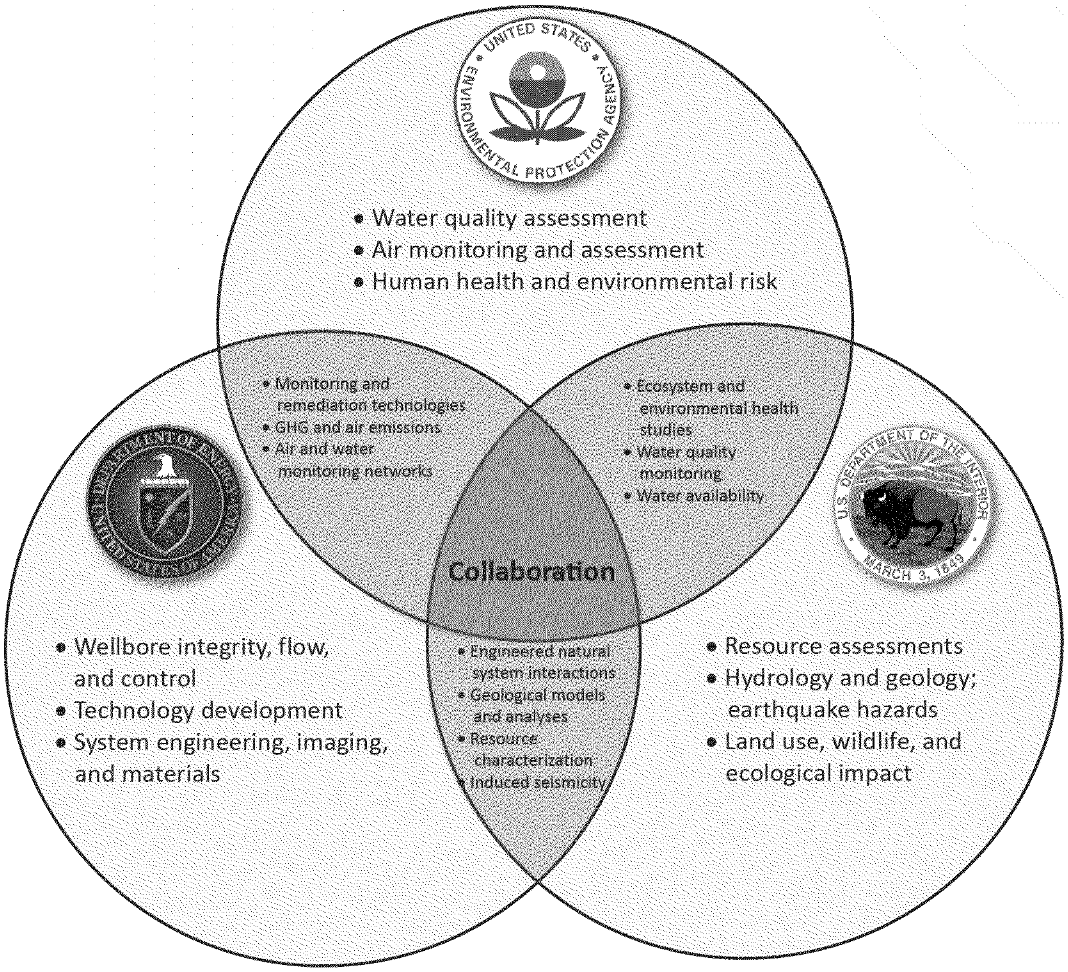
one agency will be necessary to address a particular research topic.

3. Bring coordination and consistency to these collaborating Agencies' annual budget processes. Effective research requires a sustained, well planned effort. The three Agencies will work to ensure that their annual budget processes are part of a coordinated multi-year effort with targeted and verifiable results.
4. Collaborate on coordination with stakeholders. Many organizations are involved with research on UOG resources and hydraulic fracturing related activities. The three agencies will work jointly to engage these organizations in the pursuit of collaborative research opportunities.

The DOE, DOI (notably, DOI's scientific arm, the U.S. Geological Survey [USGS]), and EPA will apply their core capabilities to evaluate and mitigate national, regional, and local impacts of UOG development and production. Through concerted cooperation, the Agencies will maximize the quality and relevance of their collaborative research, enhance synergies between the Agencies' areas of expertise, and eliminate redundancy.

To accomplish this, the Agencies will focus on working together to coordinate scientific research activities through the integrated strategy presented in this document. As laid out in a Multiagency Memorandum (Multiagency, 2012), the Agencies have agreed to develop a focused, collaborative Federal multiagency effort to address high-priority challenges vis-à-vis safe and prudent development of UOG resources. Such development will be limited to shale gas and tight gas, and shale oil and tight oil, (the latter two are collectively called "tight oil" for this discussion to avoid confusion between shale oil and oil shale resources). Beyond the scope of the topics covered in this document, the Agencies remain responsible for implementing their own authorities and internal priority-setting processes.

Figure 1: Core Capabilities of Federal Research Agencies



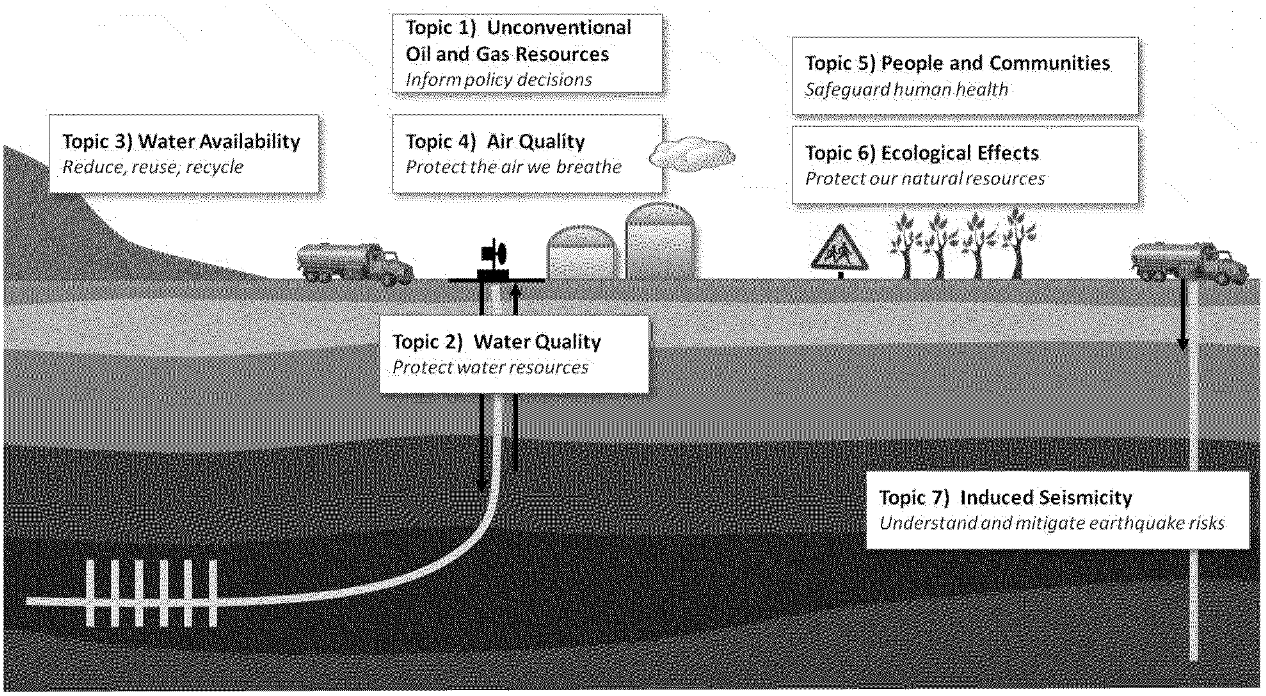
As previously discussed, the Framework presented in this document outlines a multi-federal-agency strategy to bring about sound evidenced-based decisions at the federal, state, tribal, and local levels, regarding the development of UOG resources. The document focuses on defining a research strategy that is motivated by federal safety and environmental UOG research needs highlighted in the President's "Blueprint for a Secure Energy Future" (Blueprint, 2011) and by the Secretary of Energy Advisory Board (SEAB) Subcommittee on Natural Gas (SEAB, 2011).

In addition, the research strategy recognizes that each of the Agencies has core capabilities that can guide how required research can be implemented effectively. As illustrated in the Venn diagram shown in Figure 1**Error! Reference source not found.** above, each of the Agencies has a unique set of capabilities and experience. In some cases, these core capabilities overlap, so particular emphasis is placed on a complementary strategy that avoids duplication, such that the research can be implemented efficiently. The Agencies have sought inputs from other federal agencies on relevant topical areas addressed in the Framework. The reader should keep in mind that the Framework is a living document which is subject to change, and the participating Agencies, on an ongoing basis, will solicit input from the public at large.

Research Topics

This Research Framework is divided into seven broad topical areas of UOG research needs as shown in Figure 2.

Figure 2: Multiagency Research Topics



Topic 1: <u>Understanding the scale and nature of U.S. unconventional oil and gas resources</u>: *This is a topic area which cross-cuts all other topical areas and guides and informs the environmental and health researchin the multi-agency plan.*

Topic 2: <u>Water quality</u>: *What steps must be taken to protect our water resources from potential impacts to water quality?*

Topic 3: <u>Water availability</u>: *What are the requirements to manage competing demands on water resources whose availability may be affected by UOG development?*

Topic 4: <u>Air quality and greenhouse gas (GHG) emissions</u>: *What are the relevant research questions with respect to quantifying and mitigating potential impacts to air quality from atmospheric emissions and life cycle GHG emissions associated with UOG development and production?*

Topic 5: <u>Effects on people and their communities</u>: *What are the research topics that will enable participating Agencies to understand and mitigate the potential impacts on our nation's population and communities?*

Topic 6: <u>Ecological effects</u>: *What is the research needed to understand and mitigate the* *potential impacts to ecological systems?*

Topic 7: Induced seismicity: *What are the research requirements needed to assess the potential of UOG to induce seismic events?*

What This Document Does ... and What It Does Not Do

Table 1: What this document does and does not do

What this document does	What this document does not do
Identifies research topics Each of the seven topic areas identified above contains a discussion on the primary scientific questions within the topic. *Identifies initial priorities* The Framework provides an initial prioritization of the research topics to be addressed. *Defines the roles of the three agencies* The memorandum which established this effort laid out general areas of core competency for each of the three agencies. This document provides further detail and establishes areas for leadership for each agency. The memorandum also noted that there will be areas for which the combined capabilities of more than one agency will be necessary to address a particular research topic. This document provides a framework for that collaboration. *Establishes mechanisms for interagency cooperation* As stated in the memorandum, the Steering Committee, which is leading the coordination, will be a standing entity with leadership that will rotate between the three Agencies. This document provides further detail on the roles and responsibilities of the Steering Committee and steps that will be taken to ensure that research is coordinated on an ongoing basis.	*Serve as a detailed research plan* The scope of this document is broad, covering diverse topics relevant to the safe development of unconventional oil and gas resources including well design, quality and quantity of water resources, ecology, human health effects, surface impacts, water resources, and other critical topics. Each of these topics will be the subject of future research plans that will lay out milestones and budgetary requirements in greater detail. *Provide a comprehensive analysis of ongoing research efforts outside of government* It is critical for federal research agencies to cooperate with their counterparts from industry, academia, and non-governmental sectors. While this document assesses initial research challenges, it does not provide a detailed review of efforts being carried out other than by the Agencies. Such a review will be part of subsequent research plans, and will influence which topics are addressed by the federal government. *Make regulatory recommendations* The focus of this document are research issues underlying the prudent development of domestic unconventional oil and gas resources. This document does not make recommendations on regulations. *Make recommendations for federal research beyond the Steering Committee agencies* There may be research topics that are undertaken by federal agencies not represented on the Steering Committee and therefore are not covered in this document.

Key Conclusions

The following is a summary of the key conclusions for each of the seven topic areas. **Priority Research Needs** have been identified for each of the topic areas. These represent the most critical research requirements as identified by the Steering Committee.

A key objective of this document is to define the roles and responsibilities of the three research agencies. To this end, agency-specific **Mission Capability** is indicated for each of the research needs. **Mission Capability** falls into three categories:

■	*Lead Agency*:	Agency will lead the coordination of research activities.. Research need falls directly within the agency's core competency. Agency has significant experience and capabilities relative to the research need.
▒	*Primary Support*:	Agency has significant expertise, experience, personnel, and resources to contribute to the research need.
□	*Secondary Support*:	Agency has limited (individual researchers or historical programs) or no capabilities in this area.

Each topic contains a section on **Research Leadership**, which provides further details on how the Agencies will collaborate.

Note that this executive summary lists only the highest priority items which the Agencies will address. Additional important topics are listed in the main body of the report.

Topic 1: Understanding the Scale and Nature of U.S. Unconventional Oil and Gas Resources

<u>Definition</u>

The geologic setting and mode of development of UOG resources are primary drivers of potential environmental and socioeconomic impact. This topic includes assessing the location and potential size of different UOG resources around the country in order to understand the potential scale of development in different geographical areas and geologic settings. Understanding the scale of these resources and how different development practices may affect environmental impacts requires knowledge of the geology of different basins and plays (an area in which hydrocarbon accumulations or prospects of a given type occur) and the geographical variability of geological and hydrological characteristics, such as lithology, gas/liquids ratio, reservoir pressure and other reservoir parameters, produced water content and chemistry, and others. This, in turn, will assist the federal government in understanding the overall impact of developing unconventional domestic energy resources.

Priority Research Needs and Agencies' Capabilities

Table 2: Priority Research Needs - Scale and Nature of UOG Resources

	Research Need	Mission Capability
1	***Estimate Technically-Recoverable Resource (TRR)***: Identify where assessment is needed, gather and analyze data, and report findings.	DOE DOI EPA
2	***Characterize Scale/Timelines of Development***: Analyze TRR in the context of economic factors, industry capacity, and developing technology to determine potential intensity of future drilling activity.	DOE DOI EPA
3	***Characterize Linkages among UOG Development Processes, Variable Geology and EHS Impact Pathways***: Conduct field and laboratory studies at varying scales to understand how UOG development in different reservoirs with different geologic characteristics that influence EHS impacts. Studies would include geologic characterization and 3-D mapping, reservoir performance data, in-situ (surface and underground) data collection, and other topics as developed. Map 3-D geologic frameworks in critical areas, conduct fracture analysis, and produce an atlas for continuous hydrocarbon resources of the U.S.	DOE DOI EPA
4	***Foster Technology Development for Environmental Health and Safety (EHS) Impact Mitigation***: Identify opportunities where new approaches can reduce the environmental footprint of gas/oil production, either through the development of smarter and smaller stimulations, more streamlined well/field development designs, or improved controls technology. Reduced land, air, and water impacts are expected outcomes.	DOE DOI EPA
5	***Understand Long-Term Implications of UOG Development on Co-Located Subsurface Industrial Activities or Resources***: Understand the impacts of pervasive change in subsurface environment and geologic systems resulting from natural hydrocarbon leakage and to future large-scale activities such as carbon storage.	DOE DOI EPA

Research Leadership

The DOI and DOE historically have had complementary roles in advancing the public knowledge of the magnitude of recoverable resource volumes and associated research areas. The DOI's core capability in recoverable resource assessment and geologic and hydrologic characterizations will be applied within key plays of onshore and state waters of the United States and will be key inputs to DOE's collaborative activities with the private sector in technology development. The two agencies will collaborate to target key basins where improved resource assessments and geologic and hydrologic characterizations are most needed, and for which the best opportunities exist to discern the region- and resource-specific linkages between geology, development practices, and EHS impacts. These insights will then be used to guide technology development to mitigate those impacts.

As this effort progresses, DOI will continue to lead hydrocarbon resource assessments, while DOE will focus on the advancement of relevant technology and sustainable development of resources.

Topic 2: Water Quality

Definition

Water quality encompasses a range of biological, chemical, and physical conditions for both surface (i.e., lakes and streams, as well as near-shore oceans) and subsurface waters (e.g. aquifers). Many of the public concerns regarding UOG development and production reflect uncertainty about the likelihood and potentially significant impacts on water quality in the context of both ecosystems and human well-being.

Most research to date has focused on observational studies looking for evidence that links the impact of UOG operations to water quality. Key additionalresearch needs to generate a quantitative understanding of potential impacts over the entire cycle of UOG operations (exploration, development, production, and closure) and how these impacts may vary over time and space. The goals of this research would provide better data for evaluating potential impacts (e.g., ecological, human, or community effects) and to identify best practices and new technologies for UOG operations that may help to avoid adverse impacts. An additional research goal would be to provide a technical basis for the optimum preparation and response in the event of a UOG system failure (e.g., a spill or leak) with potential adverse impacts on water quality.

Priority Research Needs and Agencies' Capabilities

Table 3: Priority Research Needs – Water Quality

	Research Need	Mission Capability
1	***Determine the Impact of Well Injection (Hydraulic Fracturing Fluids and Wastewaters) and Produced Waters on Groundwater Quality***: Conduct state of science assessments, review literature, and determine research gaps; continue retrospective and prospective case studies; conduct monitoring and modeling to establish pathways for well injection-groundwater connections; and develop analytical methods for the detection of selected chemicals reported to be found in hydraulic fracturing (HF) fluids or wastewater.	DOE DOI EPA
2	***Assess Wellbore Integrity to Minimize Contamination***: Identify materials for improved wellbore design and construction to enhance environmental performance of wellbores; apply computer models to explore the potential for gas or fluid migration from incomplete well cementing or cement failure during hydraulic fracturing in nearby wells and existing faults; and develop an Area of Review methodology for horizontal drilling similar to the methodology that is employed for vertical wells.	DOE DOI EPA
3	***Develop Mitigation Technologies***: Develop technologies for water reuse and/or recycling in order to reduce the amount of water requiring disposal through injection.	DOE DOI EPA
4	***Identify and Model Water Quality Changes Associated with UOG Life Cycle***:	

	Examine UOG impacts on groundwater and surface water quality; identify tracers that can be used to document hydraulic fracturing impacts on groundwater and surface water; establish baseline monitoring for surface water and groundwater quality and stray gas; and determine the relative source contributions and environmental pathways for contaminants associated with UOG produced and flowback wastewater.	
5	***Investigate the Transport and Fate of UOG Wastewater***: Inventory current transport and fate volumes; study impacts of direct discharge on beneficial uses; test the efficacy of wastewater treatment technologies; develop methods to detect contaminants in UOG wastewater and receiving environmental waters; and conduct Source Apportionment and Bromine Disinfection By-Product (Br-DBP) Precursor Studies.	DOE DOI EPA

<u>Research Leadership</u>EPA is leading a study of the potential effects of UOG operations on drinking water, which will include case studies of UOG operations conducted in cooperation with industry participants. DOE is executing a multifaceted research plan to increase scientific understanding of the relationship between development and potential hazards to drinking water, including microbiological transformation in on-site storage, migration of UOG produced water (a term used to describe water produced from a wellbore that is not a treatment fluid), chemical stability of waste products, and other topics. USGS is conducting baseline surface water and groundwater quality sampling and modeling to understand potential long-term trends and impacts from activities related to UOG development/ hydraulic fracturing (eg, well pad and road construction). USGS is also developing analytical methods to detect low level organic contaminants in the environment, are developing chemical environmental tracers, and quantifying exposure pathways.,

In future efforts, EPA will continue to focus on impact studies, both prospective and retrospective. DOE will lead efforts on wellbore integrity, well design, and quantify risks associated with drilling activities, including potential impacts on groundwater. DOE will also lead efforts on the development of technologies to reduce and mitigate impacts on water quality. USGS will develop groundwater flow models to determine if hydrofracture fluids and other drilling materials are contaminating water supplies and impacting ecosystems and biota, will develop analytical methods for detection of contaminants associated with produced and flowback waters in the environment, and will monitor for and characterize “stray gas”.

Topic 3: Water Availability

<u>Definition</u>
This research area relates to understanding how UOG activities may impact both the quantity and availability of water supplies. In this Framework document, the term *water availability* is used to include both the amount and the quality of water needed to meet human and ecosystem needs - so

the water availability research portfolio will be closely coordinated with the research addressing both water quality and ecological effects.

In addition, this Framework addresses both water withdrawn from surface and/or groundwater systems and water produced during the active phase of a UOG operation. Produced water is important because: 1) it can potentially be treated and reused, thereby reducing total freshwater withdrawals; and 2) it can potentially be treated and returned to the environment, thereby playing a role in the local water budget.

This research will develop the data and information that will allow for a quantitative understanding of how water availability is impacted by UOG resources, geographic locations, and methods of production. Due to the potentially large volume of data needs, this research will follow a case study approach, focusing on three regions of potential or existing UOG operations.

Priority Research Needs and Agencies' Capabilities

Table 4: Priority Research Needs – Water Availability

	Research Need	Mission Capability
1	***Provide Supporting Water Resources Information***: Support streamgage baseline monitoring in States where UOG production is ongoing and/or planned. Collect baseline information in three case study areas (Marcellus Shale, Barnett Formation, and Bakken Shale) on water resources in multiple UOG basins before, during, and after UOG operations; develop regional hydrogeologic frameworks; and identify sources of lower quality water to be used in lieu of fresh water in development activities.	DOE DOI EPA
2	***Provide Supporting Water Resources Information***: Compile published information on water withdrawals, including ancillary data.	DOE DOI EPA
3	***Develop Water Budgets***: Develop complete water budgets for sub-watersheds in each of the three case study areas, accounting for withdrawals, discharges to streams and groundwater, and characteristics ofproduced waters. Provide an	DOE DOI EPA
4	***Develop Predictive Tools***: Develop statistical models for estimating the amount of water required for UOG operations; predict volumes of flowback fluids and produced waters; develop tools to predict "pass-by" water volumes at withdrawal	DOE DOI EPA
5	***Develop Innovative Mitigation Technologies***: Develop hydraulic fracturing technologies that require less water consumption and/or alternative waterless technologies.	DOE DOI EPA

Research Leadership

The USGS Cooperative Water Program supports baseline studies on water availability and quality in a number of states where significant UOG plays have been identified. DOE is supporting site-specific studies to provide water resources information to identify the potential impacts of hydraulic fracturing water withdrawals on paired watersheds and assess shale gas drilling activity on runoff and stream flow. Ambient water quality monitoring by states and tribes, some of which is funded by

EPA, provides an additional source of background information on water resources availability and quality.

All three agencies have initiated database projects relevant to water resources: the National Water Information System, or NWIS (USGS), the Storage and Retrieval database, or STORET (EPA), and the Energy Data Exchange, or EDX (DOE). The Steering Committee will sponsor a tailored effort to identify and eliminate redundancies among these projects.

USGS will take the lead in mapping, estimating, and managing water resources and the Hydrogeologic framework. DOE will lead efforts to develop technologies that reduce the impact of UOG development on water resources, both by reducing or eliminating the use of fresh water in hydraulic fracturing and by improving the recycling of flowback fluids.

Topic 4: Air Quality and Greenhouse Gas Emissions

Definition

UOG development and operations will release various compounds into the atmosphere, including methane, sulfur, organic compounds, hazardous air pollutants (HAPs), and radon. The range of these compounds can impact humans and/or ecological resources, and some are greenhouse gases (GHGs). Key research needs in this area include improved quantitative evaluations of emissions to be used to assess ecological effects, human effects, and life cycle GHG emissions.

Priority Research Needs and Agencies' Capabilities

Table 5: Priority Research Needs – Air Quality

	Research Need	Mission Capability
1	***Air Quality Modeling***: Perform air quality modeling to evaluate potential changes in regional ozone and particulate matter (PM).	DOE DOI EPA
2	***Source Emissions Measurements***: Measure hazardous air pollutants (HAPs)/volatile organic compounds (VOCs) from well completions and surface impoundments. Apply source-receptor modeling to estimate contributions from UOG activities.	DOE DOI EPA
3	***Ambient Air Measurements***: Measure near-source ambient VOC/HAP levels.	DOE DOI EPA
4	***Exposure Assessment:*** Conduct scoping evaluation of potential for exposure to HAPS and VOCs near UOG operations.	DOE DOI EPA
5	***Emission Mitigation***: Assess the current capabilities of control strategies and measures to reduce emissions from UOG operations including extent of current use, costs and performance, availability and applicability, and operational benefits and challenges.	DOE DOI EPA
6	***Support Development of Engineering Controls, Technologies, and Strategies for***	

	Emissions Control during UOG Operations: Conduct measurement activities to provide information on performance of control technologies and practices; collaborate with industry and others to move promising control concepts to demonstration stage; and support evaluation of improved technologies and practices through field demonstrations.	DOE DOI EPA

Research Leadership

There is a growing base of information on emissions and activity data that is reported to the EPA GHG Reporting Program (EPA , 2010) and from a growing body of research studies sponsored or conducted by industry, academia, government, and even private citizens.

EPA will continue to lead these efforts, along with exposure modeling and air quality modeling. DOE will focus on sponsoring and evaluating research efforts aimed at reducing air emissions from oil and gas activities.

Topic 5: Effects on People and their Communities

Definition

Air quality, water quality, and water availability impacts from UOG production may ultimately manifest human effects, including impacts on human health and community-scale impacts. UOG development may also result in human effects related to land-use and recreation changes, and impacts on civil infrastructure.

Human health research needs include an analysis of the available data and identification of knowledge gaps; understanding of the changes in water quality, water availability, air quality, and other environmental media; knowledge of the likely human exposure and hazard scenarios; supportive toxicology related to likely exposures; the populations and lifestages susceptible to exposure and hazard; and best practices for evaluating potential cumulative risks associated with multiple stressors resulting from UOG development activities. Research needs at the community level involve characterizing UOG production impacts on community-level economics, demographics, well-being, governance, infrastructure, and services.

Priority Research Needs and Agencies' Capabilities

Table 6: Priority Research Needs – Effects on People and Communities

	Research Need	Mission Capability
1	***Current Data and Knowledge Gaps:*** Facilitate the identification of data and knowledge gaps using Comprehensive Environmental Assessment (CEA) and perform industrial hygiene surveys for assessment worker health hazards.	DOE DOI EPA
2	***Toxicity Assessment***: Perform high throughput screening value (HTSV) assessments on UOG development.	DOE DOI EPA

3	***Preliminary Health Studies and Surveillance***: Conduct health surveillance at current and proposed UOG sites and synthesize a comprehensive stressor inventory to address multiple chemical exposure routes.	DOE DOI EPA
4	***Technology Sustainability Assessment***: Integrate CEA and Health Impact Assessment (HIA) methods into existing data and comprehensively identify knowledge gaps to inform policy decisions; conduct a comprehensive literature search, computational toxicology research, and accumulate knowledge on potential health impacts.	DOE DOI EPA
5	***Community Governance, Infrastructure, and Services***: Conduct case studies of affected communities using secondary data to assess impacts.	DOE DOI EPA
6	***Economic Impacts***: Conduct case studies of affected communities using secondary data to assess impacts.	DOE DOI EPA

Research Leadership

EPA will continue to lead this research topic, coordinating as necessary with other relevant federal health agencies. Ongoing interactions among the three Agencies will be needed to coordinate the research being performed on the other components of this effort, specifically that of the water quantity and quality, air quality, and ecological effects on research areas. This coordination will include data and information collection, and resource sharing that will help support and guide the direction of the human effects research thus increasing our understanding of the impacts of UOG activities.

Topic 6: Ecological Effects

The impacts discussed in the respective air quality, water quality, and water availability topic areas may ultimately be understood as a diverse set of ecological effects across ecosystems where UOG development occurs. In addition to the three air and water impact categories discussed previously, UOG activities have the potential to adversely affect ecosystems through other impact pathways such as land use change leading to habitat fragmentation or loss, providing a vector for the introduction of invasive and non-invasive species, and adverse effects on sensitive species due to noise and light pollution.

Ecological effects research is intended to connect the media-specific findings from the air quality, water quality, and water availability research with land use change impacts, to understand their cumulative impacts on migratory birds, threatened and endangered species, fish and wildlife habitat, designated uses, and ecosystem services. Research is needed to characterize ecosystem-specific critical habitats and key indicator species and to develop monitoring networks to collect predevelopment baseline data in areas of ongoing and potential UOG activity. Pathway and cumulative ecological impact research will support resource protection, restoration, and mitigation activities so that land managers can more effectively monitor ecosystem health throughout the UOG development cycle and allow best management practices (BMP) to be refined through an adaptive management approach to reduce impacts and restore affected habitats.

Priority Research Needs and Agencies' Capabilities

Table 7: Priority Research Needs – Ecological Effects

	Research Need	Mission Capability
1	***Information Gap Analysis***: Systematically review and synthesize literature, data sources, and monitoring protocols relevant to evaluating impacts of UOG on habitats, ecosystem services, aquatic life uses, migratory birds, and threatened and endangered species; develop web site for data sharing.	DOE DOI EPA
2	***Wastewater Toxicity Testing***: Expand toxicity database with additional chemicals and species of concern; determine the toxicity of chemicals and salts used or produced during UOG activities on aquatic life; and test alternate chemicals and emerging technologies for potential environmental risks and benefits.	DOE DOI EPA
3	***Vulnerability Assessments***: Identify and prioritize key geographic regions, ecosystems and their services, sensitive aquatic communities, and critical wildlife habitats that have the greatest potential for impact from ongoing and potential UOG activities.	DOE DOI EPA
4	***Cumulative Impact Models***: Estimate total cumulative impact of the full life cycle of UOG exploration, development, and delivery on natural resource systems of concern.	DOE DOI EPA

Research Leadership

The core competencies of impact assessment, risk assessment, and adaptive management are necessary to identify, predict, and mitigate the ecological impacts from UOG development. For this reason, there is a need for close collaboration between the agencies as current research efforts proceed and planned research moves into implementation. EPA and DOI will jointly lead this area of research, with support from DOE.

Topic 7: Induced Seismicity

Definition

UOG development has the potential to induce seismic events. Researchers have long known that human actions can cause earthquake activity, from petroleum extraction to water reservoir impoundments and fluid injection into the subsurface. Current scientific understanding suggests that changes in fluid volume and pore pressure, whether they decrease through long-term fluid extraction or increase through fluid injection, can induce seismic events. Consequently, the three stages of the UOG life cycle that could potentially cause such events to occur are during hydraulic fracturing, long-term extraction, and the disposal of produced and flowback waters through deep injection wells. Current understanding suggests that the potential risk is greatest from wastewater disposal.

Although the risk of inducing seismic events from UOG operations is believed to be low, confidence can be built by demonstrating that the extensive set of empirical observations on operations to date is consistent with predictive models over a range of geologic conditions and operational parameters. Research is needed to gather further data to relate UOG operations to induced seismic events, connect these events to specific operational parameters, and develop mitigation plans for decision makers attempting to minimize seismic risks.

Priority Research Needs and Agencies' Capabilities

Table 8: Priority Research Needs – Induced Seismicity

	Research Need	Mission Capability
1	***Data Collection–Field and Laboratory***: Identify five to ten industrial sites where background and multi-year monitoring activities can be conducted; conduct background and long-term monitoring studies at the sites chosen for assessment.	DOE DOI EPA
2	***Hazard and Risk Assessment***: Analyze background data for multiple sites; develop component models for induced seismicity (IS); and develop system models for probabilistic hazards assessment.	DOE DOI EPA
3	***Physics-Based Model Development***: Develop models for predicting induced seismic events and validate models with lab experiments and field data. As predictive models are developed, they must be validated and calibrated with microseismic (<1 magnitude) field data to demonstrate effectiveness. As most field data are on the microseismic scale, models will need to be able to reproduce similar results to be validated.	DOE DOI EPA

Research Leadership

The USGS and DOE have core capabilities to contribute to these monitoring, modeling, and best practice development needs. USGS will lead efforts focused on geologic characterization and natural systems. DOE will lead efforts focused on advanced computation, advanced imaging technologies, and engineered systems.

Next Steps

This document proves a research framework, an initial set of priorities, and a process via which the Agencies will collaborate on research topics critical safely and efficiently maximizing the value of domestic unconventional oil and gas resources.

The Interagency Steering Committee which compiled this document will coordinate the efforts of the Agencies on an ongoing basis. The Steering Committee includes two members from each of the Agencies: one member focused on policy and one member focused on research and technology. The Office of Science and Technology Policy (OSTP) also contributes a member to serve on the Committee. DOE leads the Steering Committee. Leadership will pass on an annual basis among the Agencies; DOI will provide the next Committee Chair, followed by EPA.

Steering Committee has identified some critical next steps:

- *Finalize gap analyses for high priority topics.*

  The Steering Committee has identified research areas that are of particular interest, and has reviewed ongoing efforts within the three agencies. Work is also ongoing within state-based agencies, academia and industry. The goal of the Steering Committee is to ensure that the Agencies leverage external efforts, where possible, to create a more comprehensive picture of critical issues related to the development of domestic unconventional oil and gas resources. The Steering Committee will coordinate efforts of the Agencies to draw a comprehensive picture of research efforts throughout the various sectors to inform decisions on which topics must be addressed by the federal government.

- *Complete research plans*

  This document initiates the process of identifying the highest priority targets. The gap analysis detailed above will enable the Agencies to refine that analysis and steer budgets towards the most critical areas. Research plans with greater granularity will then be drafted – establishing milestones, required resources, funding sources and desired outcomes.

- *Manage research efforts on an ongoing basis*

  The Steering Committee, supported by appropriate research staff, will meet on a quarterly basis to manage research efforts, establish and track milestones, and ensure that programs are implemented in a manner that maximizes public benefit. The Steering Committee will publish an annual progress report in conjunction with the budget process. This update will provide an update on progress towards milestones and key results of ongoing research.

- *Execute continuous outreach with key stakeholder groups*

  The goal of the Steering Committee is to facilitate efforts which are useful to the various stakeholders who rely on credible, objective data to make informed decisions on resource development. This includes families who live in close proximity to drilling operations, companies who are making investments in developing the resource, regulators who are charged with crafting rules to prudently manage risks, community groups who are concerned about environmental impacts, and our nation as a whole which stands to benefit from the increased energy security and economic development that comes from prudent development of domestic resources.

  The Agencies will ensure, on an ongoing basis, that there is two way communications with these constituencies. The goal of this outreach is a) to ensure that research conducted by the federal government directly addresses the areas of greatest concern/impact, b) ensure that federal researchers appropriately leverage efforts in academia and the private sector, and c) ensure that the results of federal efforts are being effectively and transparently communicated to the public.

Summary of Research Core Competencies

Table 9: Research Core Competencies by Agency

	Department of Energy	Department of the Interior	Environmental Protection Agency
Topic 1: Understanding the Scale and Nature of U.S. UOG Resources	Conducts geologic and engineering characterization and resource modeling of frontier resources. Develops play-specific remote sensing acquisition and interpretation technologies that enable improved prospect delineation and well siting. Develops technology to minimize the environmental footprint of operations, including expertise in multi-phase flow in fractured reservoirs, as well as drilling, completion, stimulation, and production.	Evaluates and assesses both conventional and unconventional (shale gas, shale oil, tight gas, tight oil, coalbed methane) oil and gas resources. Provides detailed geologic data, information, and models of petroleum systems as well as an assessment of the potentially technically recoverable resource. Prepares geologic maps that display the detailed stratigraphic and structural geologic relationships that control hydrocarbon accumulations and possible pathways for fluid migration.	
Topic 2: Water Quality	Develops hydrogeochemical simulators and models for predicting potential changes to groundwater chemistry. Develops a wide range of new technologies and processes, including innovations which reduce the environmental impact of exploration and production such as flowback water treatment processes and water filtration technologies, alternatives to water-based stimulation, and others.	Develops new analytical methods for measuring geochemical properties, age dating, stable isotope measurement, and determination of chemical compounds in fracturing fluids Establishes baseline water quality prior to natural gas exploration and production. Projects are assessing baseline information on channel morphology, stream chemistry, benthic invertebrate and fish assemblages, and groundwater chemistry.	Conducts subsurface hydrogeological and geochemical modeling, evaluating well integrity issues, and assessing the potential for releases to groundwater from wells or surface impoundments during drilling, completion, operation, or post closure Undertakes subsurface and surface remediation of water and aquatic ecosystems polluted acutely and chronically by accidental spills and

		Conducts groundwater and surface-water sampling and flow modeling at a number of locations across the country at which gas production is underway. Examines UOG impacts on groundwater and surface water quality and identifies tracers and determines environmental pathways to document potential hydraulic fracturing impacts	releases, and in restoration in aquatic ecosystems including small streams, rivers, wetlands, and floodplains. Possesses proven expertise in monitoring infrastructure installation and experimental design to evaluate and measure ecosystem level nutrient and contaminant dynamics.
Topic 3: Water Availability	Develops alternative approaches to current hydraulic fracturing technologies that require less water consumption and/or non-potable water. Develops database resources to coordinate access to key data needs.	Provides information on the volume, quality, impacts, and possible uses of water produced during generation of oil, gas, and coalbed natural gas production and development.	Develops methods and tools for preventing or removing contaminants from surface and subsurface water sources, including wastewater.
Topic 4: Air Quality	Developed and evaluated novel imaging technologies for areal magnetic surveys for the detection of unmarked abandoned wells, and for detecting and measuring fugitive methane emissions from exploration, production, and transportation facilities Develops and applies novel monitoring technologies for air emissions. Models atmospheric processes and dynamics. Monitors baseline atmospheric signals.		Develops of ambient measurement methods; deployment, validation, and evaluation of measurement technologies; and analysis of ambient pollutant concentration data for criteria, hazardous, and greenhouse gas pollutants. Develops and applies source emission measurement methods for stationary, mobile, and area sources. Works with federal, state, and industrial partners to develop, evaluate, and apply state-of-the-art measurement methods for sources that emit criteria, toxic, and greenhouse gas pollutants. Designs and implements methods to characterize exposure to air pollutants, using field measurements and modeling

			to evaluate the relationships between source emissions, ambient concentrations, and personal exposures. Develops and utilizes plume models and source-receptor models that can link measured changes in ambient pollutant concentrations to changes in source emissions.
Topic 5: People and Communities			Develops and applies methods for evaluating toxicity of exposure to air pollutants, chemical contaminants, ranging from in vitro cell responses to in vivo testing of animal and human responses to air pollutant contaminant exposures to computational toxicological approaches. Implementation of field measurements and modeling to evaluate the relationships between source emissions, ambient concentrations, and personal exposures. Integrates information regarding hazards, exposure, and effects of stressors on human health and providing information in the form of a risk assessment for use by environmental managers and decision makers. Develops and applies multi-scale modeling systems integrating cumulative exposure and risk across multiple environmental media, multiple pathways, and multiple receptors; facilitating assessments in complexity ranging from site-specific deterministic screenings, to refined probabilistic exposure and risk

			assessments spanning the entire U.S.
Topic 6: Ecological Effects	Develops and applies novel monitoring technologies for air emissions. Models atmospheric processes and dynamics. Monitors baseline atmospheric signals.	Undertakes scientific research, monitoring, remote sensing, modeling, synthesis, and forecasting to address the effects of climate and land use change on the Nation's resources. USGS maintains 17 independent science centers and 40 university cooperative research units to conduct research in all aspects of wildlife and fisheries biology and ecology. Capabilities include basic species biology, physiology, toxicology, genetics and genomics, health and biosecurity, tracking, population assessments, habitat, and human and environmental impacts to terrestrial and aquatic species, communities, and systems.	Characterizes the physical, chemical and biological condition of ecosystems; characterizing the landscape alterations and vulnerability of ecosystems. Quantifies physical, chemical, and biological changes to ecosystems from stemming from human activities, including disruptions of ecological flows in headwater rivers, and impacts on terrestrial wildlife, stream macrobenthos, and fish. Quantifies the value of services provided by ecosystems.
Topic 7: Induced Seismicity	Develops technologies to detect critical geologic features such as natural faults and fractures. Develops and applies models to predict potential to induce seismic events and/or to propagate fractures due to injection of fluids. Models are based on detailed predictions of the geomechanical response of rocks and reservoirs during injection and its impact on pore pressures over time and space. Develops and applies of novel monitoring and imaging technologies for microseismicity.	Operates the National Seismic Network and Regional Seismic Networks in seismically active areas of the country. Operates one of the principal California Integrated Seismic Network processing centers for seismicity in central and Northern California, imports data from a 32-station seismic network under funding from DOE in cooperation with Calpine Corporation. Integrates and analyzes the Geysers geothermal data in real-time with data from USGS, UC Berkeley, and California Geological Survey seismic stations.	

		USGS hydrologists create computer models to simulate generation and maintenance of excess pore pressures in deep aquifers and their relationship to fault strength.	

Federal Multiagency Collaboration on Unconventional Oil and Gas Research

A Multi-Year Framework for Collaborative Research and Development

Introduction

Overview of Multiagency Unconventional Oil and Gas Collaboration

The Multiagency Memorandum (Multiagency, 2012) signed by the Department of Energy (DOE), Department of the Interior (DOI), and Environmental Protection Agency (EPA) (the Agencies) instructs the Agencies to develop a collaborative federal multiagency effort to address high-priority challenges in safe and prudent development of unconventional oil and gas (UOG) resources. The primary goal of this effort is to ensure coordination and collaboration between the Agencies in the development of timely, policy-relevant science and technology research results, and the design of policy options based on those results.

This multiagency collaboration addresses the need for federal safety and environmental UOG research as highlighted in the President's "Blueprint for a Secure Energy Future" (Blueprint, 2011) and by the Secretary of Energy Advisory Board (SEAB) Subcommittee on Natural Gas (SEAB, 2011). The Multiagency Memorandum was signed (April 13, 2012) at the same time as the release of the President's Executive Order for "Supporting Safe and Responsible Development of Unconventional Domestic Natural Gas Resources," which directs federal agencies to pursue multidisciplinary, coordinated research on the safety and environmental sustainability of UOG activities (Executive Order, 2012).

The federal role for UOG research will facilitate safe and prudent development of UOG resources by developing a scientific basis for sound policy and regulatory decisions that will promote "…safe, responsible, and efficient development of unconventional domestic natural gas resources…" (Executive Order, 2012).

Multiagency Management Structure

The Multiagency UOG effort is managed by a Steering Committee comprised of policy and technical leads for each agency and a representative from the Office of Science and Technology Policy (OSTP). This Research Framework is being developed through a Technical Subcommittee, comprised of scientists and engineers from each of the Agencies, with inputs from scientists from the U.S. Department of Health and Human Services (HHS).

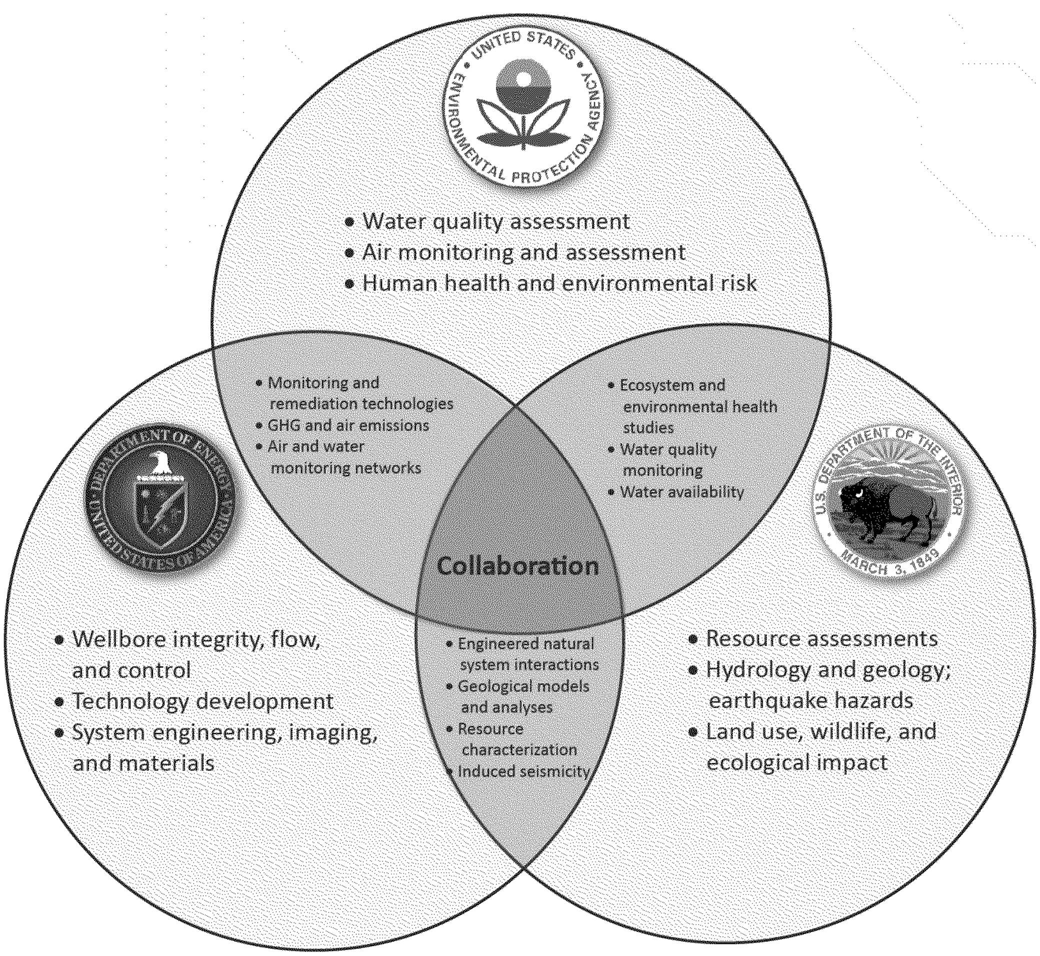
This Research Framework serves as a blueprint for efficiently and effectively directing resources as they become available to address the most critical gaps in knowledge. This Framework will guide the Agencies in designing and implementing future efforts, including the creation of detailed research plans to address priority topics. This Framework will also be instructive to managers that oversee the use of federal research resources, the policy- and decision-makers that will use the research results, and the stakeholders who will be impacted by the consequences of policies and decisions.

Cross-Cutting Technical Themes

The DOE, EPA, and the U.S. Geological Survey (USGS) - which will act as the science research arm for the DOI - will apply their core capabilities to develop the science and technology base that enables the evaluation and mitigation of national, regional, and local impacts of UOG development and production. The Agencies will develop research strategies to address resource characterization, water quality, water availability, air quality and GHG emissions, ecological effects, human effects, and induced seismicity through a collaborative approach. In addition to collaborative activities among the DOE, EPA, and USGS, interaction with other federal and state agencies will be beneficial in order to address technical and policy research needs of interest to them.

As illustrated in Figure **3** below, each of the Agencies has a unique set of capabilities and experience. In some cases, these core capabilities overlap, so particular emphasis is placed on a complementary strategy that avoids duplication, to ensure that research can be implemented efficiently.

Figure 3: Agency Core Research Competencies



The DOE's core competencies include UOG resource characterization and modeling; diagnostics and imaging technology development; drilling, completion, and stimulation technology development; wellbore integrity and flow control; air cleanup and water treatment and re-use technologies; and systems engineering, imaging, and materials.

The EPA's core competencies include ambient and source measurement of air pollutants; measurement and modeling of surface and groundwater quality, and water treatment methods and technologies; ecological causal, impacts, and services analyses; toxicological dose-response assessments; and integrated characterization of ecological and human exposures and risks.

The USGS' core competencies include energy resource research and assessment; hydrologic (both water availability and quality) research and assessments; geologic analysis including that related to induced seismicity; land use and climate change; and wildlife and fisheries ecological impact and services assessments. Each organization's core competencies are described further in the Summary of Research Core Competencies, which can be found in the table of at the end of the Executive Summary.

Collaboration with other agencies that have specific expertise and mission to address or augment various research activities will also be required. For example, an organization within the U.S. Department of Health and Human Services (HHS), the National Institute for Occupational Safety and Health (NIOSH), has the sole federal mission to conduct occupational safety and health research. NIOSH staff have participated in the development of this Research Framework.

Stakeholders

The Steering Committee will collaborate with a diverse set of stakeholders across the life cycle of UOG development and production, and will actively seek outreach opportunities as research plans are developed to address individual topics.

Key stakeholders expected to be interested in this Research Framework include, but are not limited to:

- The public, who wants to ensure that operations occurring near their homes, schools, businesses, historic sites, etc., will not adversely affect their health or property;
- Regulators and permitting entities (e.g., federal and state agencies, tribes, municipalities), who want to ensure that policy and regulatory frameworks are based on sound science;
- Public health/occupational safety and health agencies, health care organizations and practitioners, and emergency management organizations, who want to ensure that adequate protective measures are in place for rural and urban/suburban populations and for health care workers and first responders;

- Workers and labor representatives, who want to be aware of potential health hazards in the workplace;
- UOG operators and employees who want to apply the most appropriate technology, BMP, and engineering controls to reduce or eliminate hazards, to ensure that activities are conducted safely, and to make certain that monitoring strategies and plans to implement closure are carried out effectively; and
- Researchers, who want and depend on reliable information to predict effects of activities at oil and gas production sites.

Unconventional Oil and Gas Resources

Unconventional resources are those that cannot be produced economically by employing standard drilling and completion practices. The term is typically used in reference to oil and gas resources whose porosity, permeability, fluid trapping mechanism, or other characteristics differ from conventional sandstone and limestone reservoirs.

Shale oil, included here, refers to oil that can be generated and trapped within shale units. North American UOG resources exist within diverse geological and geographical settings; shale gas and tight gas resource distributions are shown in Figure 4 and Figure 5, respectively.

Figure 4: North American Shale Plays (EIA, 2012)

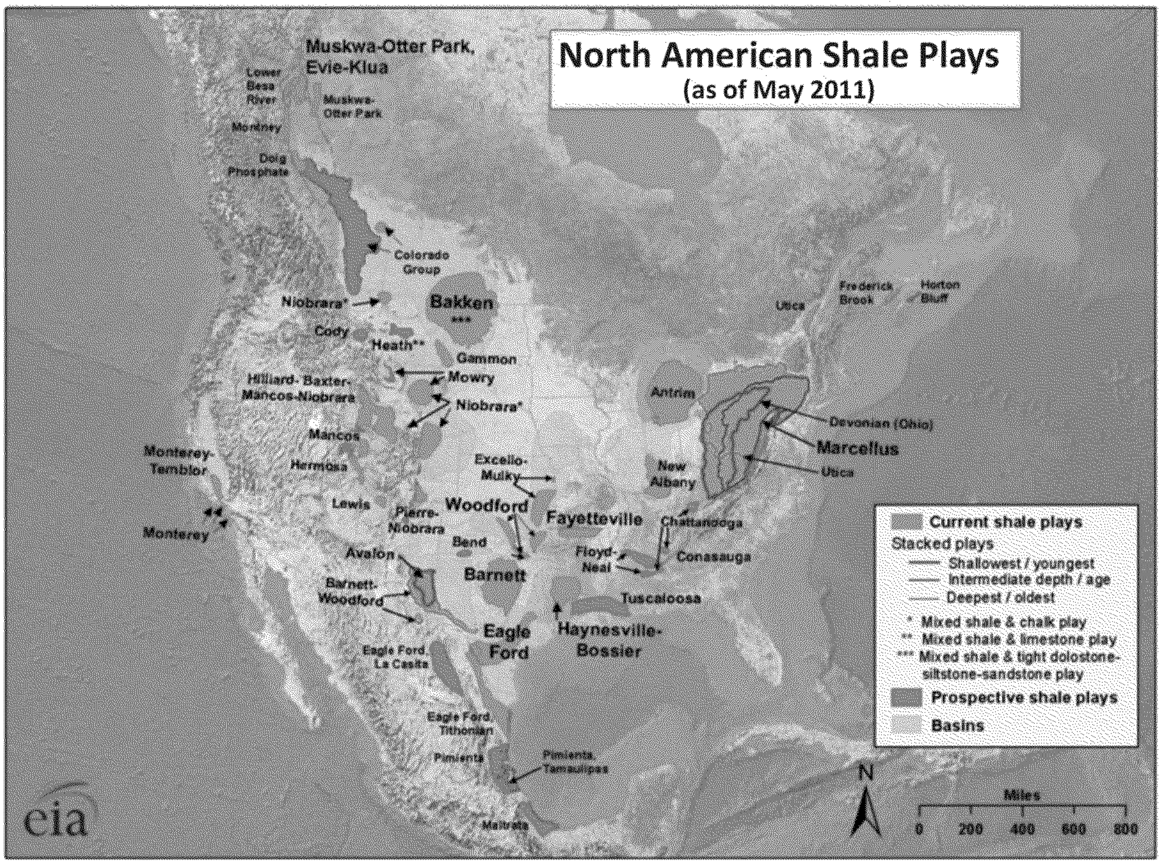
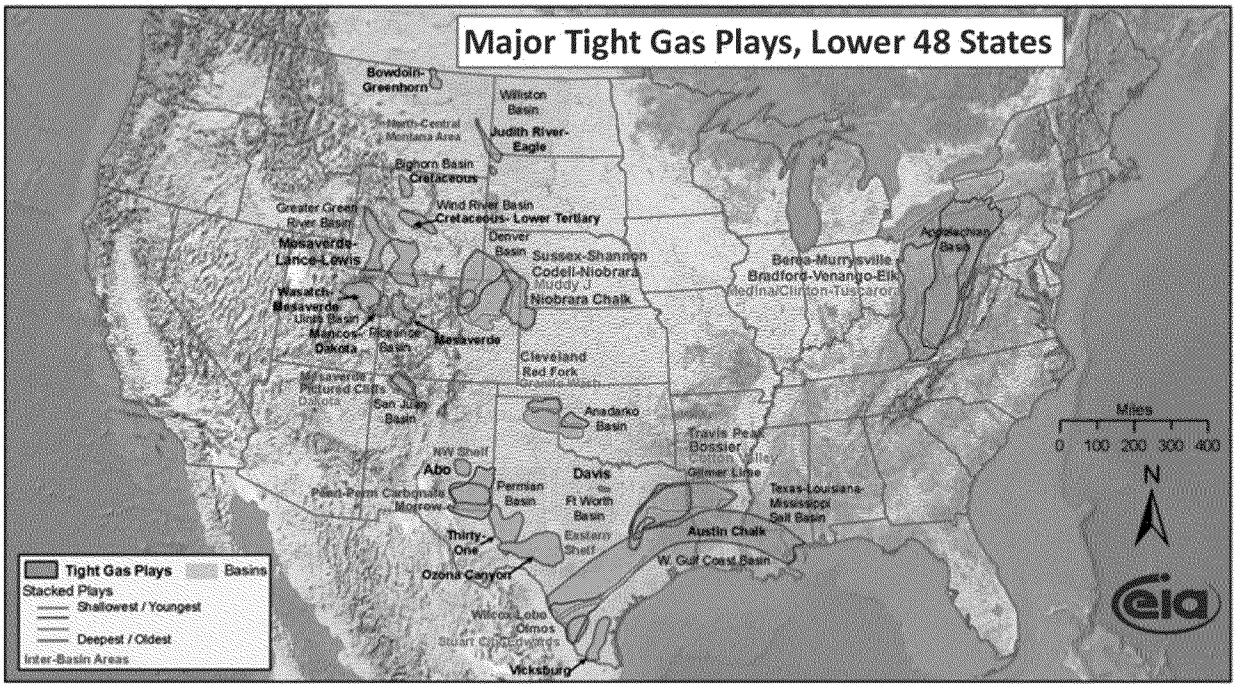


Figure 5: North American Tight Gas Plays (EIA, 2012)



Coalbed methane, shale gas, fractured reservoirs, and tight oil and gas sands are considered unconventional resources. However, this Research Framework will only address a subset of unconventional resources focusing on those rapidly-emerging hydrocarbon resources that are being brought to the earth's surface in increasing volumes primarily by the combination of deep horizontal drilling and hydrofracturing technology: shale gas and tight gas, and shale oil and tight oil, (the latter two are collectively called "tight oil" for this discussion to avoid confusion between shale oil and oil shale resources).

UOG resources require the application of specific technologies, such as hydraulic fracturing, to alter the reservoir condition and enable hydrocarbons to flow to the surface at commercially viable rates. Unlike conventional reservoirs, unconventional reservoirs, even with the application of advanced technologies, typically yield a low recovery of resources, and have highly variable and often unpredictable well performance. UOG resources have been produced safely in the United States for many decades. However, recent developments in deep horizontal drilling and massive hydraulic fracturing have resulted in a rapid and significant expansion in drilling activity across the nation.

UOG development is generally infrastructure intensive. Development of each unconventional resource presents a range of potential environmental health and safety (EHS) issues that can vary in significance among and within regions based on the geology, geography, and hydrology of the area in which they occur. This Research Framework is focused on providing information that will help to prudently develop a valuable resource and ensure safe operations, and through focused scientific research, enable decision and policymakers to have the best information available to them.

The Framework does not include the entire UOG research portfolio of each agency. For example, coalbed methane is an unconventional resource developed through hydraulic fracturing that some of the Agencies are researching. These efforts are not within the scope of this Research Framework. While such research is not considered here, this Research Framework does not preclude the individual Agencies from conducting other unconventional resource research or collaborating with the other agencies on topics that are beyond the scope of this Framework.

Generalized Life Cycle of UOG Projects

An UOG project undergoes multiple stages of development, which include:

- Geologic and geophysical site selection of well and/or well pad surveying, permitting, and well site/pad preparation (includes pits and impoundments);
- Drilling, completion, and well stimulation operations (fracturing);
- Post-fracturing flowback, pipeline installation, and production operations;
- Well site reclamation and disposal of drilling and flowback fluids and solid wastes, such as drill cuttings;
- Long-term production and disposal of produced water;
- Mining sand and gravel, and water resource allocation;
- Operations including product distribution, waste generation, disposal; and
- Closure and abandoning of the well.

Each of these development stages also includes material and personnel transport to and from well sites. One of the key processes that distinguish UOG activities from conventional activities is the use of multiple hydraulic fractures to stimulate the production of commercial volumes of oil and gas. The life cycle for this development can be divided into three phases: pre-fracturing, during fracturing, and post-fracturing.

Resource characterization and permitting are the first steps necessary prior to well siting and design. After a site is selected, and permits are issued, well pad construction activities begin. Wells then are drilled, and completed prior to the hydraulic fracturing step. Horizontal wells enable greater production at accelerated rates and are necessary in UOG production because of the relatively low recovery rates without enhanced production technologies.

Completed wells then are subjected to hydraulic fracturing, applied to stimulate production. During hydraulic fracturing, a fracturing fluid (consisting primarily of water, the fluid also contains "proppant" material and chemical additives) is pumped under high pressure through the well and into the UOG formation to create fractures within the target formation that are "propped" open by the proppant material. (DOE, 2009). The targeted resources (e.g., natural gas, natural gas liquids, and oil) are subsequently able to flow through these fractures into the production well. Water is also produced during the production phase and is composed of a combination of recovered fracturing fluid and water already in the geological formation (DOE, 2009).

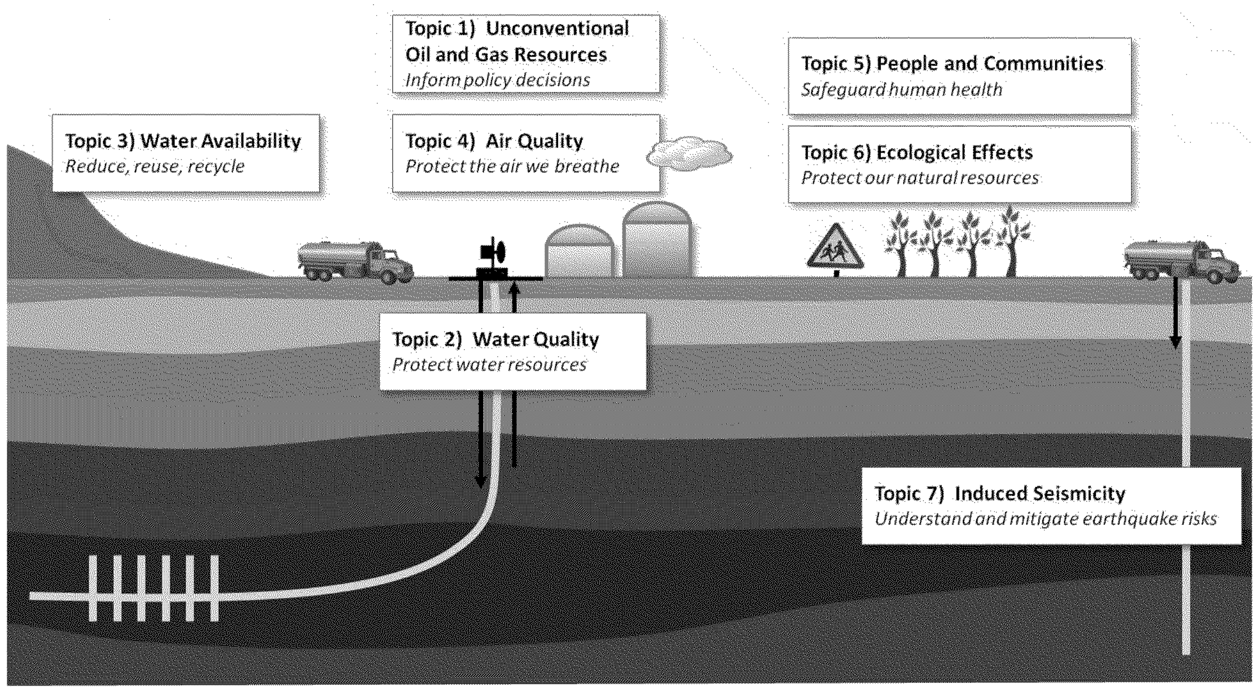
In addition to well site construction activities, various off-site activities are part of the UOG life cycle. One activity is mining sand and gravel and production of crushed stone resources that are used to develop well pad sites; sand is often used as proppant during the hydraulic fracturing stage. Sand and sandstone mining for proppant can impact communities and water quality. Other off-site activities include water sourcing, re-use, disposal, and/or treatment, and solids disposal. Some of these water-related activities may occur at a well site, although potential effects to regional water resources also need to be considered as part of the well construction and production life cycle.

Potential effects of UOG development activities will differ among and within UOG resource areas due to the influence of geographic and geological variability, differences in local ecosystems, and population demographic and densities (e.g., development in urban/suburban versus rural areas). Understanding the details of the geology and geography, as well as technological requirements is key to mitigating impacts.

Target Research Areas

The research topics targeted by this Research Framework address EHS concerns associated with exploration and production phases of UOG activities and is divided into seven broad topical areas of UOG research needs:

Figure 6: Multiagency Research Topics



Topic 1: Understanding the scale and nature of U.S. unconventional oil and gas resources: *This is a topic area which cross-cuts all other topical areas which are part of the government's multi-agency plan.*

Topic 2: Water quality: *What steps must be taken to protect our water resources from potential impacts to water quality?*

Topic 3: Water availability: *What are the requirements to manage competing demands on water resources whose availability may be affected by UOG development?*

Topic 4: Air quality and greenhouse gas *(GHG)* emissions: *What are the relevant research questions with respect to quantifying and mitigating potential impacts to air quality from atmospheric emissions and life cycle GHG emissions associated with UOG development and production?*

Topic 5: Effects on people and their communities: *What are the research topics that will enable participating Agencies to understand and mitigate the potential impacts on our nation's population and communities?*

Topic 6: Ecological effects*: What is the research needed to understand and mitigate the potential impacts to ecological systems?*

Topic 7: Induced seismicity: *What are the research requirements needed to assess the potential of UOG to induce seismic events?*

Each research area plays a role in understanding the EHS impacts of UOG development.

Topic 1: Scale and Nature of U.S. Unconventional Oil and Gas Resources

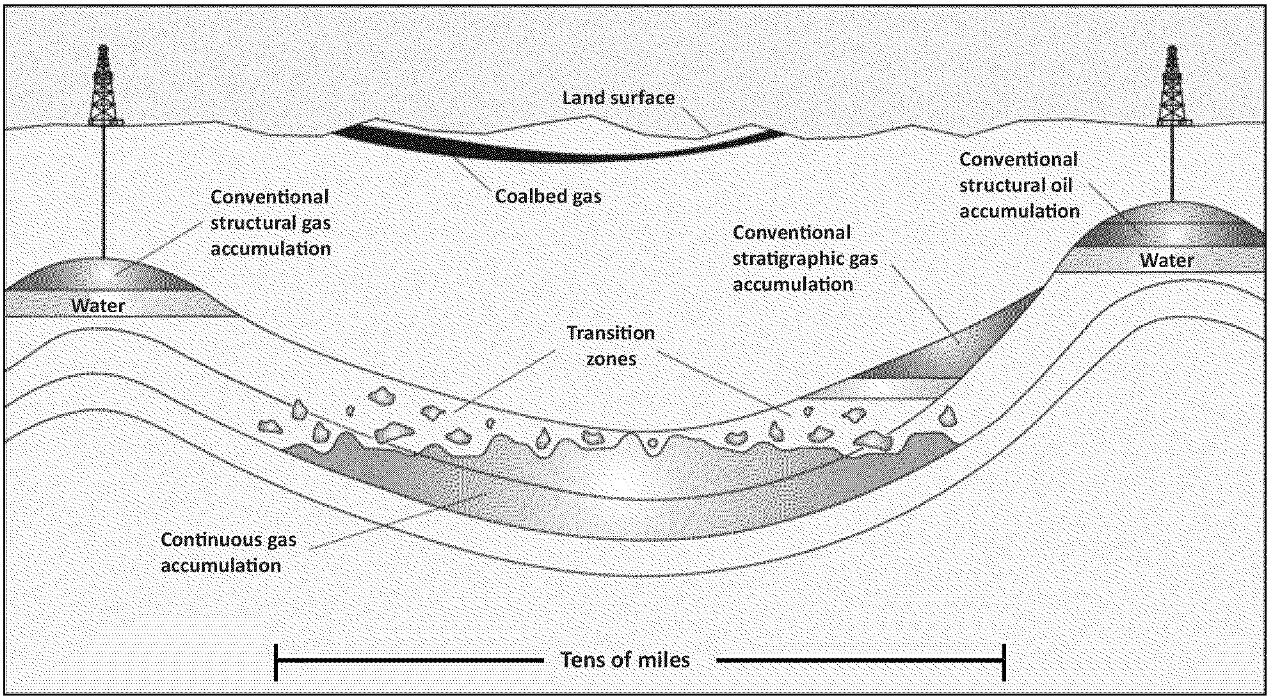
Introduction

Understanding the Scale and Nature of U.S. Unconventional Oil and Gas Resources focuses on understanding the subsurface conditions and processes that influence potential EHS impacts from currently exploited UOG basins and potential future UOG resources, as well as mitigating the impacts of developing these resources. Science-based assessment and characterization of key UOG reservoirs likely to be developed over the near- to medium-term; volumes of hydrocarbons available for production (currently and with potential technological evolution); and determination of the role of variations in geologic, hydrologic, and geographic characteristics in enabling EHS impacts are needed to. understand the linkages between development practices and EHS impacts and to mitigate those impacts through technology development

Unconventional resources are sometimes referred to as "continuous" resources, because they are more homogenously distributed in a geologic unit at a larger spatial scale than conventional resources. However, as discussed above, unconventional resources cannot be produced economically through standard drilling and completion practices, and therefore require the application of advanced technologies, such as hydraulic fracturing (also referred to as hydrofracturing), to alter the reservoir condition and enable hydrocarbons to flow at commercially viable rates. Unconventional resources are commonly regional in extent, have diffuse boundaries, and are not buoyant on a column of water.

In contrast to unconventional reservoirs, conventional reservoirs are discrete accumulations with well-defined hydrocarbon-water contacts, where the hydrocarbons are buoyant on a column of water. Conventional accumulations commonly have relatively high matrix permeabilities, generally favorable reservoir properties and relatively high recovery factors, obvious seals and traps, and discrete field boundaries. A schematic of the general differences between conventional and unconventional resources is found in Figure 7.

Figure 7: Conventional vs. Continuous (Unconventional) Hydrocarbon Resource Accumulations (Modified from Schenk and Pollastro, 2002)



Unconventional accumulations have very low matrix permeabilities, do not have obvious seals and traps, are in close proximity to source rocks or are the source rocks themselves, are commonly under higher pressure than conventional sources, and have relatively low recovery factors (the percentage of the resource that can be recovered) with existing technologies. Unconventional or continuous oil and gas accumulations typically include hydrocarbons that occur in tight oil and gas reservoirs, shale gas and shale oil reservoirs, basin-centered reservoirs, fractured reservoirs, and coal beds. However, this Research Framework will only address a subset of all unconventional resources that are being brought to the earth's surface primarily by the combination of deep horizontal drilling and hydrofracturing technology: shale gas and tight gas, and shale oil and tight oil, (the latter two are collectively called "tight oil" for this discussion to avoid confusion between shale oil and oil shale resources).

Key Science Questions

Understanding the nature and scale of potential EHS impacts from UOG resource development, as well as mitigating the impacts of developing those resources, requires detailed science-based characterizations to help answer the following questions:

1) What and where are the key UOG reservoirs likely to be developed over the near- and medium-term?

2) What are the volumes of hydrocarbons potentially available for production, both currently and in the future, as technologies improve?
3) What are the current and future technologies and practices that will be used to safely access UOG resources in an environmentally sustainable manner?
4) How do key geologic, hydrologic, and geographic characteristics vary among and within UOG reservoirs, and how can development practices be optimized in light of this variation to mitigate potential EHS impacts?
5) What are the possible ranges in the intensity of development of shale gas, tight gas, and tight oil resources, given assessed resource volumes and uncertainty regarding future market conditions, regulatory frameworks, and technology development?

These questions are designed to guide research to place site-specific EHS impact assessments in an appropriate national context, as well as to identify opportunities in which advancement of UOG development technology and approaches might significantly mitigate the potential for EHS impacts. In addition to EHS impact assessments, research is required to understand the fundamental geologic parameters that control the formation and occurrence of UOG resources, such as lithology, geologic structure and history (pressure/temperature conditions), and existing lithospheric stress conditions.

Current State of Knowledge

Stimulation/Fracturing Technologies

The use of stimulation/fracturing technologies to access unconventional formations is not new. In the United States, initial development of shale gas fields began in the 1920s in the Upper Devonian Huron Shale (Big Sandy Field) of eastern Kentucky and southern West Virginia (Ley, 1935). This early production was enabled by numerous means of formation stimulation, including explosive fracturing with gelatinized nitroglycerin. Hydraulic fracturing has also been in practice in vertical wells for more than half a century, and was first applied to the development of the Huron and other Eastern gas-containing shales beginning in the 1950s (Boswell, 1996). Beginning in the mid-1970s, recognition of very low recovery factors (<10 percent; Brown, 1976; Avila, 1976) and the massive remaining in-place resources in gas shales in the eastern United States resulted in a research and development public-private partnership (PPP) including private operators, DOE and the Gas Research Institute (GRI) to further expand commercial production from the Huron Shale. This PPP led to advances in deep horizontal drilling, multi-stage fracturing, and slick-water fracturing. The progressive development, through similar government-industry partnerships, of improved downhole drilling motors, downhole mud-pulse telemetry equipment, microseismic monitoring, and other technologies have also played a key role in enabling expanded tight oil and shale gas production (SCNGO, 2007).

Improvements in today's shale gas production were provided in the 1980s and 1990s when Mitchell

Energy and Development Corporation, in cooperation with DOE's National Energy Technology Laboratory (NETL), brought deep horizontal drilling and large-scale hydraulic fracturing technologies together in the Barnett Shale in North-Central Texas. By 2005, the Barnett Shale was producing almost half a trillion cubic feet per year of natural gas, and the approach was quickly exported to the Fayetteville Shale in North Arkansas, as well as the Haynesville, Marcellus, Woodford, Eagle Ford and other shales. A recent newspaper article, co-authored by George Mitchell (of Mitchell Energy), concluded the use of hydraulic fracturing to produce shale gas is the "…most significant development in the U.S. energy sector in generations…" (Bloomberg and Mitchell, 2012).

Resource Spectrum

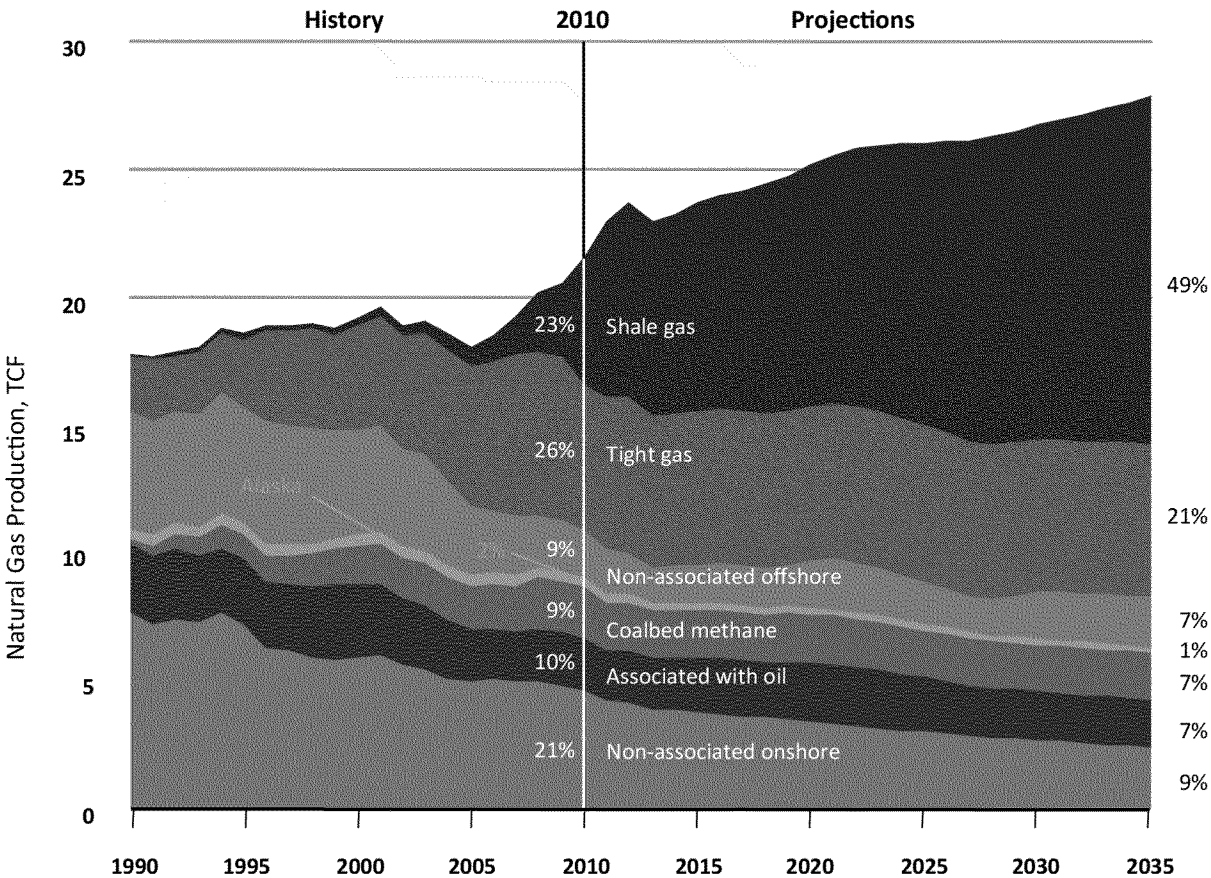
Understanding the potential EHS impacts of UOG development requires knowledge of reservoir characteristics, as well as the amounts of available resources in different accumulations and how likely they are to be produced in the near- to medium-term. Resources are commonly divided into three main categories:

- <u>in-place resources</u>, which include all of the gas thought to exist in a given geological zone, is generally irrelevant to the discussion of production potential (particularly with respect to unconventional resources) other than to provide a theoretical upper bound;
- <u>technically recoverable resources</u> (TRR) which describe the volumes available for production using known technologies, but without specific regard to commercial viability; and
- <u>economically recoverable resources</u> (ERR) which is that sub-set of TRR that can be developed profitably given prevailing market conditions.

Current and Future Production

In the past decade, shale dry gas (consisting primarily of methane) production in the United States has grown from 0.39 trillion cubic feet (TCF) in 2000 to 4.80 TCF in 2010, (23 percent of U.S. dry gas production). The Energy Information Administration's (EIA) latest projection suggests shale gas will approach one-half of total U.S. gas production by 2035 (Figure 8) and that shale gas and tight gas will combine to provide 70% of total production.

Figure 8: U.S. Natural Gas Production History and Projections from 1990-2035, in TCF (EIA, Annual Energy Outlook, 2012)



Even with the significant growth in the production of these unconventional resources, much has yet to be learned about them, and it is important to remember that each reservoir behaves differently and has unique characteristics. There is a great deal of uncertainty associated with the information regarding these resources – resource assessments, forecasts of growth, what effect these resources will have, how they will behave, how long reservoirs will be productive, and so on. For example, the EIA's assumptions (Annual Energy Outlook, 2012) for per well productivity continue to evolve, recognizing much wider possible ranges in well performance, as well as typically lower Estimated Ultimate Recovery (EUR) than prior estimations. Furthermore, such substantial revisions, both positive and negative, should be expected, as the first substantive drilling information from emerging basins becomes available and many key factors, such as recovery factors, the potential areal variability in well performance, the impact of sustained low prices, and the potential impact of future technology becomes better understood.

Resource Assessments

Assessing future production volumes and their potential location requires detailed regional analysis of resource size. The USGS assessments provide estimates of the TRR within key plays of onshore and state waters of the U.S. The Bureau of Ocean Energy Management (BOEM) provides the same type of assessments for the nation's Outer Continental Shelf (OCS). These assessments provide information on the ultimate productive geographic areas and hydrocarbon volumes expected, assuming development occurs with technology and practices similar to those used currently. Other organizations produce resource estimations of varying types, including estimates of all the resource that may be present in known formations (in-place resources); however, these are typically not conducted in the rigorous, consistent, and transparent manner needed to guide decision making. Assessments of gas in-place are often the cause of confusion, especially given the historically low recovery typical of unconventional resources. Consequently, these assessments can be expected to significantly overstate resources realistically available from any given play.

The USGS produces resource assessments of both conventional and unconventional oil and gas resources. However, given the increasing pace of UOG development, attention has been focused of late on these UOG resources and their potential development impacts. Maps showing undiscovered, technically recoverable unconventional oil resources, shale gas, and tight gas can be found in Figure 9 through Figure 11, below. There are no estimates of UOG resources offshore in the U.S. OCS.

Figure 9: Mean Estimates of Undiscovered, Technically Recoverable Unconventional Oil Resources in the United States

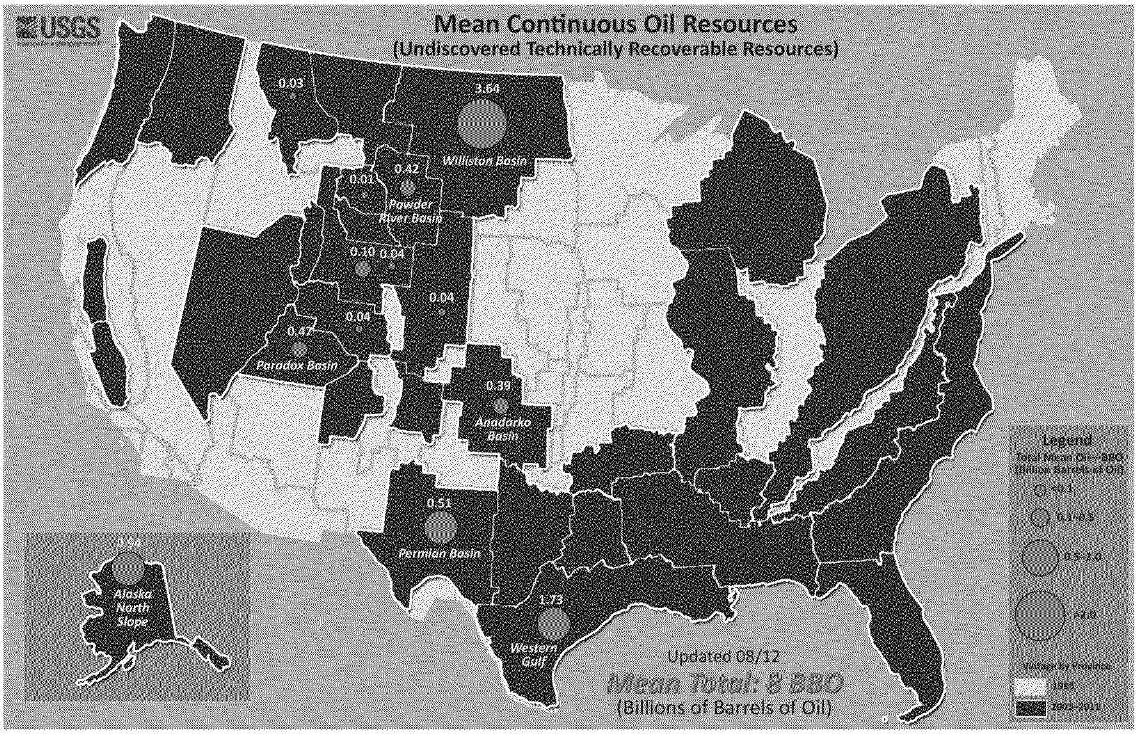


Figure 10: Mean Estimates of Undiscovered, Technically Recoverable Shale Gas Resources in the United States

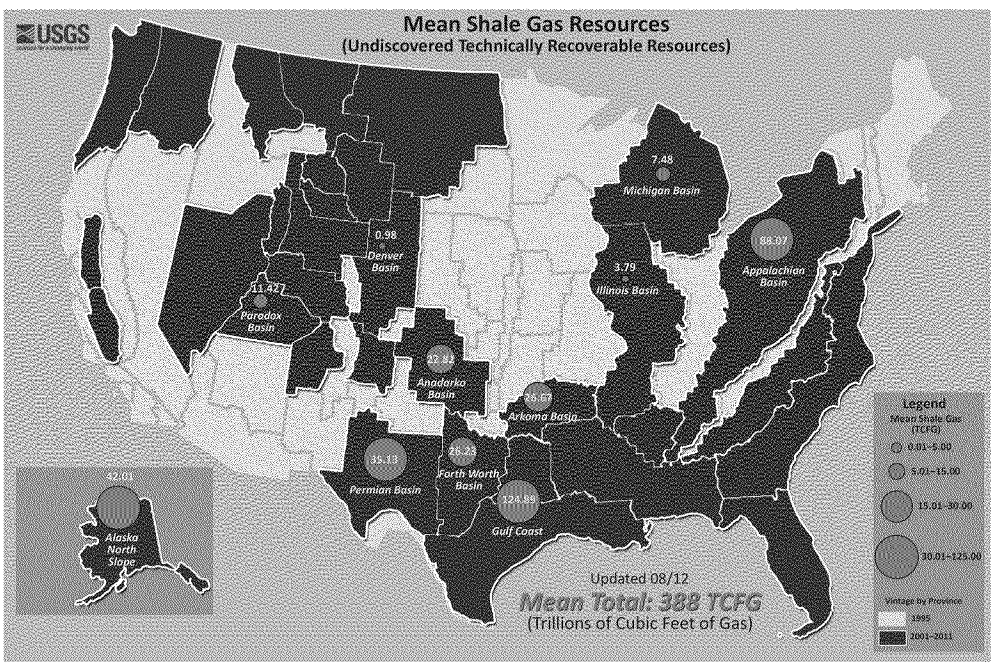
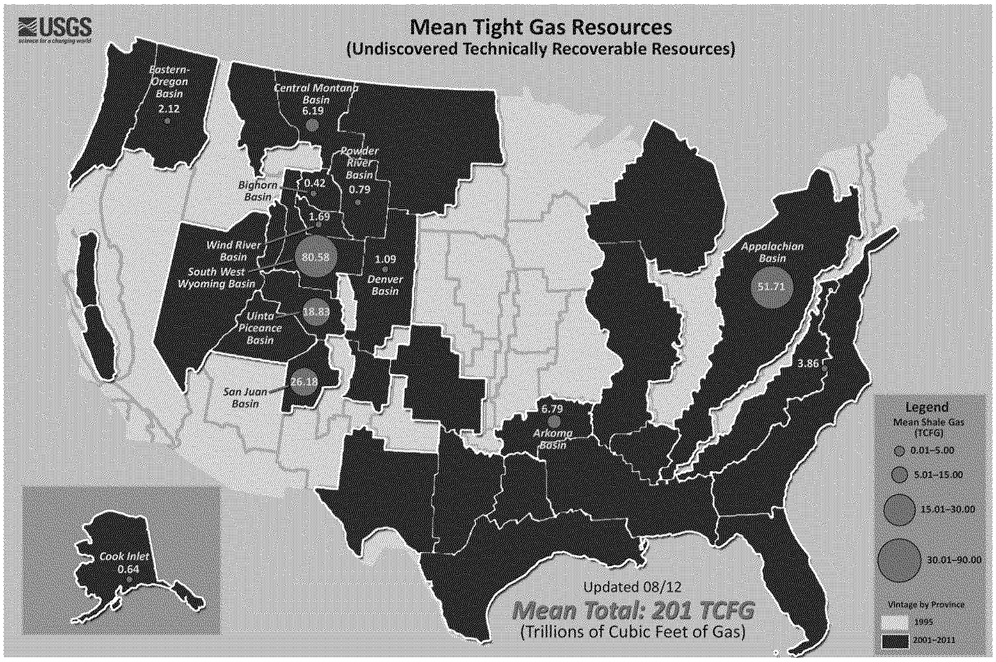


Figure 11: Mean Estimates of Undiscovered, Technically Recoverable Tight Gas Resources in the United States



Reserve Estimates

The EIA surveys approximately 1,200 domestic oil and gas operators annually, and this serves as the basis for estimates of U.S. proved reserves of crude oil, natural gas, and natural gas liquids. The EIA reports specifically track the impact of drilling, production and price changes on reserves in six major shale gas plays (Barnett, Haynesville/Bossier, Fayetteville, Woodford, Marcellus, and Antrim). At the end 2010, shale gas reserves totaled nearly 100 BCF.

Research Needs: Topic 1 (Understanding the Scale and Nature of UOG)

Table 10: Research Needs - Understanding the Scale and Nature of UOG

Line of	Research Need	Participating Agencies (lead in bold)
Resource Assessment	***Estimate Technically-Recoverable Resource (TRR)***: Identify where additional assessment is needed, gather and analyze data, and report findings.	**DOI**
	Conduct Reserve Assessments: Estimate current reserves for key plays/regions to predict future production amounts and determine what plays are likely to be developed over the near- and mid-term in line with the mission of the Energy Information Administration (EIA). This information will be useful in long-term planning of domestic resource production and can help in estimating allocation of resources for permitting, R&D, etc.	**DOE**

	Characterize Scale/Timelines of Development: Analyze TRR in context of economic factors, industry capacity, and developing technology to determine potential intensity of future drilling activity.	**DOE,** DOI
Development Impact Characterization	***Characterize Linkages among UOG Development Processes, Variable Geology, and EHS Impact Pathways***: Conduct field and laboratory studies at varying scales to understand how UOG development in different reservoirs with different geologic characteristics influences EHS impacts. Studies would include geologic characterization and 3-D geologic mapping, reservoir performance data, in-situ (surface and underground) data collection, and other topics as developed. Map 3-D geologic frameworks in critical areas, conduct fracture analysis, and produce an atlas for continuous hydrocarbon resources of the U.S.	DOE, **DOI,** EPA
	Study interaction between UOG development and variable subsurface environment (various geological and engineering parameters).	DOE, **DOI**
Resource Management	***Foster Technology Development for EHS Impact Mitigation***: Identify opportunities where new approaches can reduce the environmental footprint of gas/oil production, either through the development of smarter and smaller stimulations, more streamlined well/field development designs, or improved controls technology. Reduced land, air, and water impacts are expected outcomes.	**DOE**
	Understand Long-Term Implications of UOG Development on Co-Located Subsurface Industrial Activities or Resources: Understand impacts of pervasive change in subsurface environment and geologic systems resulting from natural hydrocarbon leakage and to future large-scale activities such as carbon storage.	**DOE,** DOI

Summary of Topic 1

DOI and DOE historically have played complementary roles in advancing the public knowledge of recoverable resource volumes and associated research areas. Fundamental to understanding EHS effects of UOG development is the need for an improved understanding of the extent of UOG plays and volumes of resource potential within them, as well as detailed understanding of the geologic conditions of the reservoirs and characteristics of the interaction between those reservoirs and the development process.

The DOI's core capability in geologic characterization and recoverable resource assessment will be applied to key plays of onshore and state waters nationwide. For example, DOI will collaborate with the State Geological Surveys to prepare geologic maps that will improve our understanding of the structural and stratigraphic relationships that control, in part, UOG occurrences and potential pathways for fluid flow. Studies such as these will be a key input to DOE's collaborative activities with the private sector in technology development. Both agencies will collaborate in key/priority basins where resource assessment and geologic characterization is most needed to enable a better understanding of the potential future scale of UOG development and where detailed studies can provide insights into the manner in which development practices interface with variable subsurface conditions to create harmful EHS impacts. The insights gained from these studies will provide guidance for technology development to mitigate those impacts.

DOE, with the support of its EIA will focus on information related to current reserves and projections of future production. DOI, on the other hand, will be the primary source of technically recoverable resource assessments as well as many of the key geologic and engineering parameters that enable production forecasts.

Topic 2: Water Quality

Introduction

This research topic focuses on understanding the near-term and long-term water quality impacts of UOG production on surface and groundwater resources. This research addresses the implications of pollutants associated with UOG production and waste byproducts interfacing with the nation's water resources. This will include research on pollutant measurement and modeling to understand fate, transport, and migration through surface water, hydrogeologic structures, and geochemical processes, as well as the development and promotion of technologies to mitigate water quality impacts through prudent well design to ensure wellbore integrity and early detection of unanticipated leakage.

For the purposes of this Framework, the term "water quality" refers to the biological, chemical, and physical conditions of a body of water. The body of water may be on the surface (e.g., lakes, streams, rivers) or below the surface (e.g., aquifers). Improper well construction and wellbore integrity can lead to contamination of these bodies of water. Changes in water quality can have direct and indirect effects on ecosystems and human well being. Many of the public concerns regarding UOG production revolve around concerns regarding the likelihood and potential significance of impacts on water quality. This chapter describes the key research needed to address such concerns.

Key Science Questions

The following are key science questions related to water quality impacts associated with UOG activities that need to be addressed:

1) What changes in water quality resulting from the UOG production life cycle are most likely to affect water system sustainability?
2) Where are those changes most likely to occur?
3) What practices, technologies, or actions would make the UOG-water system more sustainable, i.e., reduce/prevent future significant changes to key water quality parameters?
4) What actions can be taken to mitigate or remediate instances where UOG operations have already or will impact water quality?

In this context, "changes" include basic water quality parameters, such as flow volume, temperature, pH, conductivity, turbidity, sediment load, nutrient loadings, and dissolved inorganic carbon, as well as the presence, fate, and transport of chemical, microbial, or biological contaminants. Contaminants may be constituents of water associated with UOG production, such as flow-back or production water, or may be naturally occurring elements mobilized by changes in chemical conditions caused by intrusion of UOG-production-associated water into natural water bodies (e.g., arsenic associated with aquifer solids mobilized by organics or other reduced compounds in the flow-back or production water).

Changes may be quantified in terms of magnitude, temporal, or spatial distribution. "UOG production" includes the entire cycle of UOG operations, i.e., construction of infrastructure (road and pipeline networks, drilling pads, holding ponds, power plants), operations (traffic, drilling, worker activity), fluid mixing, injecting/fracturing, water capture/holding/reuse/transport, treatment/disposal of hydraulic fracturing (HF) water, and other HF materials. "Water system sustainability" includes environmental, economic, and social impacts (including public health).

All industrial systems are subject to occasional accidents and failures, even when best practices are followed. The research associated with *Key Science Question 4* above should focus on how to best prepare and respond to system failures when they do occur so that damage to water quality can be minimized. This research will address the issues that are often of greatest concern to local populations who want to know what possible changes to water quality and quantity are most likely to occur in their particular locale. This research should also investigate how UOG production can best be done in a manner that avoids adverse impacts on water quality. Emphasis should be placed on developing sets of recommended practices and development of new technologies applicable to different environmental conditions in order to enable the safe and sustainable extraction of UOG resources while avoiding or minimizing unintended consequences.

Current State of Knowledge

There is a large and growing body of scientific literature relating to the existence and magnitude of impacts of UOG production on water quality. Most research-to-date has focused on observational studies looking for evidence of association between UOG operations and impacts to water quality. For example, Osborn et al. (2011) analyzed groundwater samples from 68 private water wells in northeastern Pennsylvania and upstate New York and reported an association between active UOG operations and methane contamination of drinking water. Molofsky et al. (2011) later examined water samples from 1,700 wells in the same area of Pennsylvania and found that methane was statistically more likely to occur in water wells located in valleys. Assuming that valleys are located in areas where the underlying strata are more fractured (and more erodible), Molofsky and his colleagues offer an alternative suggestion that natural fractures, not UOG activities, are responsible for methane detected in these wells. Warner et al., (2012) suggested there is other geochemical evidence for natural upwelling of deep waters along fractures. Analyses of the water quality of some produced waters show that the radium content of oil- and gas-field produced waters in the northern Appalachians (particularly the Marcellus Shale) have elevated levels of salinity and radium (Rowan, et al., 2011). The occurrence of methane in water wells is a growing public concern. Studies of carbon and hydrogen isotopic evidence for the origin of combustible gases in water supply wells in north-central Pennsylvania have been conducted by Revesz, et al. 2010.

Data tying contamination directly to UOG operations is limited. Some of the most recent research articles are published in highly regarded journals (e.g., Entrekin et al. 2011, Warner et al. 2012) and EPA documents highlighting to Dimock, Pennsylvania and Pavilion, Wyoming have received a great deal of attention because there are very little other data available. Entrekin's research established that construction effects are degrading water quality and Warner ascertained that the UOG in Pennsylvania is occurring in a region with greater risk to drinking water.

Rozell and Reaven (2011) assessed the risk of water pollution associated with different steps in UOG operations and concluded that wastewater management posed the greatest potential risk to water quality. Researchers have examined other potential pathways of water quality impacts including spills on site, leaks through wellbores during the fracturing process, migration of fracturing fluids or deeper formation brines through natural or artificial fissures connected to groundwater supplies, leaks or spills of flowback and produced water returned to the surface, and impacts of wastewater when returned to the natural environment.

Due to the direct discharges of produced water in the western United States,, the Bureau of Reclamation's (BOR) Technical Service Center gathered data from publically available sources to describe the water quality characteristics of produced water, performed an assessment of water quality in terms of geographic location and water quality criteria of potential beneficial uses, identified appropriate treatment technologies for produced water, and described practical beneficial uses of produced water (BOR, 2011). Produced water quality varies significantly based on the geographical location, the type of hydrocarbons produced, and the geology and geochemistry of the producing formation. In general, the total dissolved solids (TDS) concentrations are from 5,000 milligram per liter (mg/L) to 100,000 mg/L, but can range from 100 mg/L to over 400,000 mg/L compared to EPA's Secondary Maximum Contaminant Level (SMCL) of 500 mg/L. Silt and particulates, sodium, calcium, chloride, and bicarbonate are the most commonly occurring dissolved inorganic constituents in produced water. Benzene, toluene, ethylbenzene, and xylenes (BTEX) and polycyclic aromatic hydrocarbons (PAHs) compounds are the most commonly occurring organic contaminants in produced water (Kharaka and Hanor, 2007). The types of contaminants found in produced water and their concentrations will dictate the most beneficial use, if any, and the appropriate type, degree, and cost of treatment required.

Critics of these and similar studies contend that observational and theoretical studies are not sufficient to prove cause-and-effect relations between UOG operations and adverse outcomes to water quality. However, conducting properly designed experiments in the classical sense would require randomization, controls, and consideration of confounding factors such as seasonal, geologic, and climatic variation. Careful design of observational studies can help control for confounding factors, supporting causal inference. For example, the EPA is currently conducting a study of the potential effects of UOG operations on drinking water (U.S. EPA, 2011). One component of the EPA study plans to use case studies of UOG operations conducted in cooperation with DOE, USGS, State agencies, and UOG companies who will allow water quality monitoring before, during, and after hydraulic fracturing operations. Pairing these measurements with those from a similar location that does not experience hydraulic fracturing can provide particular case-specific data regarding effects to water quality from a known source under a best-case scenario.

Currently, DOE is executing a multifaceted research plan to: 1) characterize the chemical and microbiological transformations that occur in produced water during on-site storage, 2) detect and mitigate unwanted migrations of produced water in the near-surface environment (spills) and at depth (zonal migration), 3) investigate the chemical stability (permanence) of produced water treatment sludge and drill cuttings when disposed in landfills, 4) develop large-scale survey methods to locate existing oil and gas wells that, if inadequately plugged, can provide a conduit for the rapid vertical migration of produced water, and 5) evaluate the effectiveness of current methods of protecting groundwater from contamination during various stages of UOG operations (drilling, casing, cementing, and production). The DOE and its Regional University Alliance (RUA) partners are identifying natural tracers in produced water that permit these waters to be detected when commingled with surface waters and underground sources of drinking water. The DOE is also developing novel geochemical tracer techniques for monitoring water contaminants. This timely research can assist in accurately determining or tracing a particular water contaminant to the right source.

The USGS is actively developing a monitoring tool with the ability to measure methane and other volatile hydrocarbons in streams in order to detect changes due to UOG operations. The technique recently was piloted in a multi-day experiment in Utah. This research has focused on using in-stream measurements to determine the quantity (Heilweil et al., 2012), timing (Sanford et al., 2012), and source (Revesz et al., 2012) of the methane that is dissolved in groundwater discharging to the stream. As dissolved methane and other volatile gases including hydrocarbons and environmental tracers exsolve (separate at a critical point in temperature) into the atmosphere, ongoing research has been focusing on understanding the timing of this degassing within various stream environments (Solomon et al., 2006; Stolp et al., 2010). Streams act as an integrated signal in time and space for changes in water quality throughout the entire watershed. Being able to detect changes in various concentrations in a stream can improve our ability to detect changes and their potential sources before the site of the release is even discovered can thus serve as a powerful monitoring tool. In addition, the isotopic signature of the methane in the stream or wells can be used to distinguish biological from thermogenic sources (Osborn et al., 2011).

Research Needs: Topic 2 (Water Quality)

Table 11: Research Needs – Water Quality

Line of	Research Need	Participating Agencies (lead in bold)
Determine The Impact of Well Injection And	Conduct state of science assessments, review literature, and determine research gaps.	DOE, DOI, **EPA**
	Continue retrospective and prospective case studies.	DOE, DOI, **EPA**

Quality:	Conduct monitoring and modeling to establish pathways for well injection-groundwater connections.	DOE, DOI, **EPA**
	Develop analytical methods for the detection of selected chemicals reported to be found in HF fluids or wastewater. Conduct geochemical analyses of UOG produced waters to determine the occurrence of and geologic controls for salinity and naturally occurring radioactive materials	DOE, DOI, **EPA**
Assess Wellbore Integrity to Minimize Contamination:	Identify materials for improved wellbore design and construction to enhance environmental performance of wellbores.	**DOE**, EPA
	Apply computer models to explore the potential for gas or fluid migration from incomplete well cementing or cement failure during hydraulic fracturing nearby wells and existing faults.	**DOE**, EPA
	Develop Area of Review methodology for horizontal drilling. The Area of Review (AoR) is the area (on a map) that is impacted by production operations, which determines the potential environmental impact regions. Methods for determining AoR for vertical wells are well established, but a corresponding methodology for horizontal wells does not exist.	**DOE**, EPA
Technology Development	Develop mitigation technologies for water reuse and/or recycling in order to reduce the amount of water requiring disposal through injection.	**DOE**
Identify and Model Water Quality Changes Associated with UOG Life Cycle:	Examine UOG impacts on groundwater and surface water quality.	DOE, **DOI**, EPA
	Identify tracers that can be used to document hydraulic fracturing impacts on groundwater and surface water.	DOE, **DOI**, EPA
	Establish baseline monitoring for surface water and groundwater quality and stray gas.	DOE, **DOI**, EPA
	Determine the relative source contributions and environmental pathways for contaminants associated with UOG produced and flowback wastewater.	DOE, **DOI**, EPA
Investigate the Transport and Fate of UOG Wastewater:	Inventory current transport and fate volumes; develop methods to detect contaminants in UOG wastewater and receiving environmental waters.	DOE, DOI, **EPA**
	Study impacts of direct discharge on beneficial uses.	DOE, DOI, **EPA**
	Test the efficacy of wastewater treatment technologies.	DOE, DOI, **EPA**
	Conduct Source Apportionment and Bromine Disinfection By-Product (Br-DBP) Precursor Studies.	DOE, DOI, **EPA**
Predicting/ Responding to System Failures	Systems analysis to assess, predict, prevent system failures (e.g. wellbore failure, existing wellbores).	**DOE,** DOI, EPA
	Effective practices for responding to system failures (e.g. mitigating leakage pathways) to ensure the impacts from such failures are minimized.	**DOE,** DOI, EPA

Summary of Topic 2

The DOE, DOI, and EPA all possess core capabilities in evaluating the effects of UOG development on water quality. Through this Framework ,they will collaborate on addressing main research needs related to changes in water system sustainability, locations where water quality changes are most likely to occur, preventive actions to preserve water quality, and mitigation measures for remediation of water resources affected by UOG development.

The DOE's capabilities in systems-level integrated assessments require an understanding of produced and flowback water quality and knowledge of groundwater and surface quality changes due to UOG development. DOE is executing a multifaceted research plan to increase scientific understanding of the relationship between UOG development and potential hazards to drinking water, including microbiological transformation in on-site storage, migration of produced water, chemical stability of waste products, and other topics. In addition, DOE has capabilities to develop new technologies aimed at improving wellbore integrity, casing, and cementing that will assist in preventing accidental release of contaminants to groundwater.

DOI's capabilities in characterizing produced and flowback waters and determining baseline water quality conditions aligns well with EPA's focus on measuring and modeling surface and groundwater quality, environmental characterization, and quality control of samples. This Research Framework incorporates existing EPA water quality research project findings. EPA is leading a study of the potential effects of UOG operations on drinking water to include case studies of UOG operations conducted in cooperation with industry participants.

In addition, DOE and EPA collaboration to develop water treatment technologies and water remediation techniques will aid in developing preventive tools for protecting water quality and mitigating effects of UOG development. This work will best proceed as a partnership involving those federal and state agencies responsible for planning and overseeing environmental cleanups, along with the various private sector environmental engineering companies engaged to conduct operations.

Topic 3: Water Availability

Introduction

This topic focuses on understanding water accessibility from surface and groundwater resources for multiple uses such as drilling and hydraulic fracturing for UOG.. Topical research will include how UOG activities affect water availability, the settings and timeframes in which these changes may occur, the magnitude of the impacts and the aspects of water quality that are affected, and any actions (such as best practice recommendations and new technology development) that may be taken to mitigate the potential impacts.

Key Science Questions

There are several key science questions related to the consequences of UOG activities on water availability that need to be addressed:

1) What aspects of UOG activities affect water availability?
2) Where (in what settings) and when will those effects most likely occur, and how long do they persist?
3) What is the magnitude of these impacts, and what aspects of water availability are affected?
4) What actions can be taken to mitigate these potential impacts?

These questions are designed to guide research toward the development of information needed to make astute decisions regarding UOG operations and water availability. In this context, water availability means the right amount of water at the right time and of the right quality to meet human and ecological needs. It follows that there are strong linkages among *water availability, ecological effects,* and *water quality*, and research on these three topics that will need to be closely coordinated. Moreover, water availability includes both the water withdrawn from surface sources and/or groundwater sources for operations together with the water produced from aquifers and brought to the surface during the production phase of UOG operations. In this context, produced water includes both formation water and flowback water (return of injected water to the surface when injection pressure is released). Information on produced water is important from a water availability perspective because: 1) produced water can be treated and used in subsequent HF operations, thereby reducing freshwater withdrawals, and 2) produced water can be treated and returned to the environment, thereby playing a role in the local water budget.

Current State of Knowledge

Research on the environmental risks of UOG operations is particularly lacking in the area of water availability. Surface water and groundwater monitoring networks exist for water availability and quality, but these are not always in the right locations for UOG activities. Limited data have been compiled for the development of regional hydro-geologic frameworks. Requirements are evolving for the type of water supply needed for hydraulic fracturing (potable vs. non-potable, salty vs. fresh), but virtually no assessments have been conducted on the availability of these lower-quality water resources.

The amount of water used and produced in UOG operations is a function of the type of hydrocarbon formation (e.g., shale, tight sands), the geographic location of the resource (including regional climate and competing water demands), and the method of production (e.g., injection-fluid properties and well construction and design) (GAO, 2012). Impact assessments of UOG operations on various aspects of water availability have been conducted in a limited number of locations, notably in the Appalachian Basin (Soeder and Kappel, 2009) and in Texas (Groat and Grimshaw, 2012; Nicot and Scanlon, 2012). Results from these studies are useful for the specific location in which the study was conducted but are difficult to generalize to other locations because of variations in the types of data collected and the methods used in collection. The impacts of UOG operations on water supplies will also be influenced by regional climate (i.e., arid or moist), local hydrologic conditions, such as drought, and other demands on the water supply. These and other factors must be considered in an assessment of water availability.

A few reports have been published on the amounts of water required for shale gas hydraulic fracturing, volumes recovered as flowback fluid, and the consumptive loss of fracking water that remains downhole, but there is a dearth of information for tight/shale oil plays. Development of predictive tools has not advanced much beyond estimates based on previous experience. Finally, with respect to mitigation measures, a very limited amount of research has been conducted. There are some industry data on water supply and disposal practices, as well as limited data from the Environmentally Friendly Drilling program.

Research Needs: Topic 3 (Water Availability)

Table 12: Research Needs – Water Availability

Line of	Research Need	Participating Agencies (lead in bold)
Water Resources Data Collection	***Provide Supporting Water Resources Information***: Support streamgage baseline monitoring in States where UOG production is ongoing and/or planned. Collect baseline information in three case study areas (Marcellus Shale, Barnett Formation, and Bakken Shale) on water resources before, during, and after UOG operations	DOE, DOI, **EPA**

	Provide Supporting Water Resources Information: Develop regional hydrogeologic frameworks and identify sources of lower quality water to be used in lieu of fresh water in development activities.	DOE, DOI, **EPA**
	Provide Supporting Water Resources Information: Compile published information on withdrawals, including ancillary data.	**DOI**, EPA
	Design and implement a program to provide consistent information to assess effects of UOG operations.	DOE, DOI, **EPA**
Water Withdrawals and Produced Waters	***Develop Water Budgets***: Develop complete water budgets for sub-watersheds in each of the three case study areas, accounting for withdrawals, discharges to streams and groundwater, and produced waters.	DOE, **DOI**
	Update produced water databases to better allow fingerprinting of the produced water to definitively determine whether contamination in groundwater or surface water comes from UOG flowback water.	**DOE**, DOI
	Collect and geochemically fingerprint time-series fluid samples from three case study areas to develop a methodology that can be extended to many locations where data is known.	DOE, **DOI**, EPA
Tools and Resources	***Develop Predictive Tools***: Develop statistical models for estimating the amount of water required for UOG operations.	**DOI,** EPA
	Develop Predictive Tools: Develop statistical models to predict volumes of flowback fluids and produced waters.	**DOI,** EPA
	Develop a regional hydrogeologic framework for each of the three case study areas.	DOE, **DOI**, EPA
	Develop coupled groundwater-surface water models for each of the three case study areas.	**DOI**
	Predict the combined effects of water withdrawals and discharges of produced waters.	**DOI**
Mitigation Measures	***Develop Innovative Mitigation Technologies***: Develop hydraulic fracturing technologies that require less water consumption and/or alternative waterless technologies.	**DOE,** EPA

Summary of Topic 3

Through ongoing interactions among the three Agencies, research relating to water availability will be coordinated with research on water quality and human and ecosystem effects to develop a comprehensive picture of the environmental, public health, and community impacts associated with UOG operations. Coordination and flexibility also will be required in order to adjust this research plan to new data and information on UOG activities and water availability. All three Agencies have tabase projects relevant to water resources: DOE Energy Data Exchange (EDX). USGS National Water Information System (NWIS), and EPA Storage and Retrieval database, (STORET).

The USGS Cooperative Water Program supports baseline studies on water availability and quality in a number of states where significant UOG plays have been identified. The DOE is supporting site-specific studies to provide supporting water-resources information. This will include identification of potential impacts of hydraulic fracturing water withdrawals on paired watersheds and assessments of shale gas drilling activity on runoff and stream flow. Ambient water quality monitoring by states and tribes, some of which is supported by the EPA, provides an additional source of background information on water resources.

USGS will lead efforts on stream gage monitoring, mapping, estimating, and managing water resources. DOE will lead efforts to develop technologies to reduce the impact of unconventional oil and gas development on water resources, both by reducing or eliminating the use of fresh water in hydraulic fracturing, and by improving the recycling of flowback fluids.

Topic 4: Air Quality and Greenhouse Gas Emissions

Introduction

This topic focuses on identifying, monitoring, and mitigating UOG production's impact on air quality and the emission of GHG. This research area intends to improve the scientific understanding of the rate of generation and fate of air pollutants that can impact regional air quality, contribute to GHG emissions. An additional goal of this research is the development of appropriate mitigation strategies. Stakeholder partnerships that support improved monitoring, measurement protocols, and data analysis will also be developed.

Key Science Questions

The following are key science questions related to air quality impacts and GHG emissions associated with UOG activities that need to be addressed:

1) What are the criteria pollutant, HAP, and GHG emissions of UOG activities relative to existing conventional oil and gas operations?
2) What are the impacts of UOG activities on site, local, and regional air quality?
3) What practices associated with UOG activities contribute to human and environmental exposures to air pollutants?
4) What are the acceptable levels of these impacts, and what technologies and operational approaches can be adopted or developed to prevent their occurrence and to address these impacts when they exceed these levels?

These questions are designed to guide the research toward the development of information needed to make informed decisions regarding UOG operations. Five lines of investigation have been identified to address these key science questions: 1) source emissions characterization; 2) ambient air measurements; 3) air-quality modeling; 4) exposure assessments; and 5) mitigation practices and technologies. These lines of investigation are described in more detail below.

Current State of Knowledge

There are significant gaps in the knowledge base of air pollutant and GHG emissions from UOG operations, their incremental impacts on air quality and exposures, and their potential risks to human and ecological health. There is, however, a growing base of information on emissions and activity data that is reported to the EPA GHG Reporting Program (U.S. EPA, 2010), the New Source Performance Standards for oil and gas operations (U.S. EPA, 2012a), and from a growing body of research studies sponsored or conducted by industry, academia, and government.

There have been considerable efforts to understand the GHG emissions over the UOG life cycle from resource development through end use, including those by Howarth, et al., 2011; Alvarez et al., 2012; Cathles, 2012; Weber and Clavin, 2012; and Skone, 2011. Numerous studies have evaluated ambient concentrations of pollutants associated with unconventional and conventional oil and gas operations, among which are the Colorado Department of Public Health and Environment and Agency for Toxic Substances and Disease Registry 2008; Lazor 2010; and Eastern Research Group and Sage Environmental Consulting, 2011.

Several studies have focused on exposure and health risk, including those by the Colorado Department of Public Health and Environment and Agency for Toxic Substances and Disease Registry, 2010; Zielinska et al., 2010; Ethridge, 2011; McKenzie et al., 2012. Several studies of air quality emissions from oil and gas operations have also been published, including Modrak et al., 2012; Pétron et al., 2012; and Thoma et al., 2012. However, neither emissions nor the air quality impacts of upstream oil and gas operations have been as well-characterized as other sources, such as electric power generation, and many opportunities remain to improve our understanding of the air quality impacts of these activities.

There is a need for additional emission measurements that provide robust information about how emissions may change under differing production and operating conditions (e.g., wet gas vs. dry gas, and use of "green completion" techniques). Measurements that can be used to improve and verify emission models for sources such as storage tanks and impoundment ponds are also needed.

Ambient air quality measurements are needed to better characterize the composition and amounts of air pollutants and the pattern of variability in those pollutants that occur over the course of drilling and UOG production activities. Ambient measurements are also needed to evaluate how source emissions contribute to ambient pollutant concentrations and for sources such as diesel emissions that are not amenable to source testing.

There are no known studies that have modeled the local and regional air quality impacts of UOG operations, which leaves a significant gap in our understanding of air quality impacts. Studies of exposures and health risks associated with air pollution from UOG operations are currently limited. Those that are available point to the need to include modeling of short- and long-term exposures as well as collection of site, area, residential, and personal exposure measurements data and data needed for modeling, particularly for peak short-term emissions (McKenzie et al., 2012).

Research Needs: Topic 4 (Air Quality and Greenhouse Gas Emissions)

Table 13: Research Needs – Air Quality and Greenhouse Gas Emissions

Line of	Research Need	Participating Agencies (lead in bold)
Air Quality Modeling	***Air Quality Modeling***: Perform exploratory air quality modeling to evaluate potential changes in regional ozone and PM.	**EPA**
	Apply source-receptor modeling.	**EPA**
	Near-source dispersion modeling of HAP/VOC concentrations.	**EPA**
	Modeling to estimate effects on regional air quality.	**EPA**
Source Emissions Measurements and Controls	***Source Emissions Measurements***: Measure VOCs/HAPs from well completions and surface impoundments.	DOE, **EPA**
	Source Emissions Measurements: Apply source-receptor modeling to estimate contributions from UOG activities.	DOE, **EPA**
	Support Development of Engineering Controls, Technologies, and Strategies for Emissions Control during UOG Operations: Conduct measurement activities to provide information on performance of control technologies and practices.	**DOE**, EPA
	Support Development of Engineering Controls, Technologies, and Strategies for Emissions Control during UOG Operations: Collaborate with industry and others to move promising control concepts to demonstration stage.	**DOE**, EPA
	Support Development of Engineering Controls, Technologies, and Strategies for Emissions Control during UOG Operations: Support evaluation of improved technologies and practices through field demonstrations.	**DOE**, EPA
	Develop source "fingerprints" for source-receptor models.	DOE, **EPA**
	Improved emission models for tanks and ponds.	DOE, **EPA**
	Investigate emissions of inorganic compounds.	DOE, **EPA**
	Characterize emissions of NOx, PM, and VOCs from diesel engines.	DOE, **EPA**
Ambient Air Measurements	***Ambient Air Measurements***: Measure near-source ambient VOC/HAP levels.	DOE, DOI, **EPA**
	Measure ambient concentrations of HAPs/VOCs at critical locations (e.g., schools, residential areas, etc.).	DOE, **EPA**
	Measure regional ambient ozone and PM concentrations.	DOE, DOI, **EPA**
Assessment of Exposure to UOG-Related Air Pollutants	***Exposure Assessment***: Perform scoping evaluation of potential for exposure to VOCs and HAPs near UOG operations.	**EPA**
	In-depth exposure modeling.	**EPA**
	Investigate potential exposures from indoor sources.	**EPA**
Air Pollutant and Greenhouse Gas	***Emission Mitigation***: Assess the current capabilities of control strategies and measures to reduce emissions	**DOE**, EPA

Mitigation	from UOG operations, including extent of current use, costs and performance, availability and applicability, and operational benefits and challenges.	
	Revise emissions estimates for life cycle analyses with knowledge of uncertainty parameters.	**DOE**, EPA

Summary of Chapter 5

Air quality research will be coordinated with other investigations enabled through this Framework to develop a comprehensive picture of the environmental and public health impacts associated with UOG development. Agency coordination will require development of detailed research activities that account for differences in operations and conditions in the various resource plays, variations in human population proximity, characteristics, and ecosystem types.

EPA is the lead agency for air quality research. For ambient air measurements, EPA brings core capabilities in source emissions measurements; air quality, source receptor, and exposure modeling; and analyses of ambient samples.

DOE's capabilities include a highly-instrumented, mobile sampling trailer that can be quickly transported to locations of interest. In air quality modeling activities, expertise from both DOE and DOI will be needed to evaluate possible air quality impacts associated with such future development. For exposure modeling and measurement activities, DOE and DOI can provide information based on their competency areas to help guide the EPA exposure assessment studies.

Topic 5: Effects on People and their Communities

Introduction

This topic focuses on identifying, characterizing, prioritizing, and monitoring both the potential human health effects on community and worker populations as well as impacts on the community's well-being. This section is broadly separated into two major research areas: 1) Human Health Impact Research Needs; and 2) Community-scale Impact Research Needs. The objectives of the first research area are to improve our understanding of the potential human health effects, and to identify and fill data gaps within this area. The objectives of the second research area will focus on understanding the social, economic, and psychological impacts due to UOG development, how these impacts affect communities, and methods to mitigate these impacts.

Overall the research will focus on examining and assessing completed, on-going, and newly proposed and approved research. This research will inform risk and sustainability assessments for safely managing the development of UOG resources and communicating these risks in a community setting. In addition, this research builds upon data and knowledge from the air quality, water quality, and water availability research areas and relevant toxicology, in conjunction with human health research, to assess potential human health risks and to understand, prevent, and mitigate potential environmental health risks that are realized on a regional scale. Research in this area will also contribute to a comprehensive understanding of how changes brought about by UOG activities can affect not only the health of community residents and and UOG workers but also a community's infrastructure, services provision, its local government, and overall quality of life..

Outputs of this research will help to identify areas for future scientific inquiry and provide information to support the roles and decision making of federal public health agencies, industry, and state and local governments and agencies. Research will also address topics related to understanding socioeconomic impacts and benefits realized by communities, and methods to mitigate these.

Key Science Questions

Human Health Key

Of highest priority is identifying the key research related to understanding the potential community and worker human health effects associated with UOG activities. The key science questions and drivers are:

1) What are the current data and knowledge gaps with respect to exposures, toxicology, and human health effects research? How is human health and risk information collected, communicated, and perceived by impacted communities and workers?

2) What changes in water quality, water availability, air quality, local surface soils, and other environmental media as well as other changes in the physical environment (e.g., traffic, noise, seismic activity, etc.) from UOG production activities are most likely to impact human health?

3) What are the exposures, including complex mixed exposures, and hazard scenarios that are likely to occur within human populations exposed to UOG production activities?

4) What populations and lifestages are the most likely susceptible to exposure and hazard as a result of UOG production activities?

5) What is the current best practice for evaluating potential risk associated with all stressors from all sources as a result of UOG production activities? Is this approach applicable to assess potential exposure scenarios associated with UOG production activities?

Community Scale

The following are key science questions related to community scale impacts associated with UOG activities that need to be addressed:

1) What are the demographic and economic changes associated with UOG development?

2) How does the life cycle of UOG production activities impact local and regional economies?

3) How do UOG production activities impact local governance, infrastructure planning, and social service provision?

4) What are the effects of these stressors on community well-being? Are these effects realized disproportionately by various subpopulations within communities?

These questions are designed to guide the research toward the development of information needed to make decisions regarding potential human and community scale effects related to UOG operations.

Current State of Knowledge

Human Health Impacts

Although the current state of knowledge in several areas is limited, the results from research on current and past UOG production activities and chemicals used in UOG activities are still highly useful. For instance, toxicity reference value (TRV) databases exist that are used by federal and state agencies for risk management. These TRVs may be available for different routes of exposure and media (i.e., oral and inhalation; water and air) and exposure duration (acute, subchronic, and chronic). Analysts can identify and prioritize potential hazards, exposure scenarios, exposure levels, and cumulative risks associated with UOG production by combining these TRVs with local and national exposure estimates, or existing chemical use information from sources such as FracFocus or the courts.

As with many emerging environmental health issues, the concern regarding UOG production activities is multidimensional, spanning potential exposure to known and unknown hazards on one axis, with potential socioeconomic impacts on the other axes. Due to the complexity and the interplay among these dimensions, the traditional risk assessment paradigm may be inappropriate. Instead, a technology sustainability assessment approach must be taken, which, as described in greater detail below, will utilize a framework to systematically structure information from across human and environmental health coupled with economic and social considerations. This Framework then provides the foundation for structured decision-support methods to engage diverse stakeholders in identifying and prioritizing risks and benefits associated with UOG production activities (National Research Council, 2011). Such clear input from stakeholders can then inform decision-makers across a variety of sectors (e.g., industry, government) and scales (e.g., community, state, and federal) in determining how to maximize UOG benefits while mitigating impacts to human health and communities.

Community Scale Impacts

Existing knowledge of UOG community impacts is limited, and the most relevant research is drawn from analogous industrial activities. Existing research on the impacts of other resource extraction (e.g., logging, mineral mining, conventional oil and gas production) suggests a set of potential UOG community impacts (Boxall et al., 2005). However, the unique characteristic of UOG production activities may limit direct comparisons to other industrial economic and social analyses. Efforts are underway to examine the impacts of shale gas exploration on surrounding property values (Boxall et al, 2005), providing evidence of economic benefits associated with production (Weber 2012, Marchand 2012). Numerous unpublished case studies document local fiscal impacts of UOG drilling on farming, tourism and other economic sectors.

To more thoroughly understand the potential community-scale impacts of UOG production activities, some parallels can be drawn to other resource extraction (e.g., logging, mineral mining) activities, such as increased economic activity, potential for temporary or sustained economic growth, damage to existing roadways due to increased vehicular weight/overweight vehicle usage, changes in real estate values, the local tax base, health facilities, school systems, and demographic profiles. However, UOG development and production activities have distinctly unique characteristics as well, such as the increased use of heavy machinery, development of drilling platforms, and the need to dispose of large volumes of waste water.

Research Needs: Topic 5 (Effects on People and Their Communities)

Table 14: Research Needs – Effects on People and their Communities

Line of	Research Need	Participating Agencies (lead in bold)

Data Assessment	***Current Data and Knowledge Gaps***: Facilitate identification of data and knowledge gaps using Comprehensive Environmental Assessment (CEA)	DOI, **EPA**
	Current Data and Knowledge Gaps: Perform industrial hygiene surveys for further assessment of worker health hazards.	DOI, **EPA**
	Identify non-regulated contaminants of concern in air, including indoor air, and water from prior investigations.	DOI, **EPA**
Toxicity Assessment	***Toxicity Assessment***: Perform high throughput screening value (HTSV) assessments on UOG development.	**EPA**
	Perform additional in vitro and in vivo laboratory-based studies on chemicals in or exposures of concern per priority order.	**EPA**
	Develop toxicity screening values for chemicals of concern.	**EPA**
Preliminary Health Studies and Surveillance	***Preliminary Health Studies and Surveillance***: Conduct health surveillance at current and proposed UOG sites and synthesize a comprehensive stressor inventory to address multiple chemical exposure routes.	**EPA**
	Perform monitoring and modeling of current exposures at UOG sites.	**EPA**
	Perform appropriately controlled retrospective epidemiological studies.	**EPA**
Technology Sustainability Assessment	***Technology Sustainability Assessment***: Integrate CEA and Health Impact Assessment (HIA) methods into existing data and comprehensively identify knowledge gaps to inform policy decisions.	DOI, **EPA**
	Technology Sustainability Assessment: Conduct a comprehensive literature search, computational toxicology research, and accumulate knowledge on potential health impacts.	DOI, **EPA**
Community Governance, Infrastructure, and Services	***Community Governance, Infrastructure, and Services***: Conduct case studies of affected communities using secondary-data to assess impacts.	**EPA**
Economic Impacts	***Economic Impacts***: Conduct case studies of affected communities using secondary-data to assess impacts.	**EPA**
	Characterize short- and long-term impacts on: 1) incomes of those with and without resource ownership, 2) employment, 3) housing markets, and 4) other industries.	DOE, **EPA**
	Identify economically vulnerable and disproportionately impacted populations.	DOE, **EPA**
Exposure and Hazard Scenarios	Integrate and synthesize data from across the research program on a rolling basis.	**EPA**
	Develop site prioritization methods based on human exposure potential.	**EPA**
	Identify public health intervention and exposure mitigation measures.	**EPA**
Human	Biomonitor blood and urine to measure human	**EPA**

Biomonitoring	exposures to chemicals associated with UOG activities.	
	Develop biomarkers for health effects that may be associated with UOG, including pre-clinical changes.	**EPA**
Current Best Practice(s) for Evaluating Potential Risk	Utilize newly proposed approaches for addressing other risk issues (e.g., Multipollutant Science Assessment, cumulative risk assessment) to identify potential human impacts from UOG production activities.	DOE, DOI, **EPA**
	Develop methods and guidelines for assessing health risks associated with exposures to chemical mixtures and their application to UOG production activities.	DOE, DOI, **EPA**
Health Studies	Synthesize a comprehensive stressor inventory to address multiple chemical exposure routes and physical hazards such as light, noise, traffic, and explosions.	**EPA**
	Develop prospective epidemiological surveillance systems and health effect studies.	**EPA**
	Initiate studies of long-term impacts for all vulnerable populations prior to well development.	DOE, DOI, **EPA**
	Conduct HIA.	DOI, **EPA**
Human Health and Community-Scale Impacts	Characterize indirect health effects of UOG activities as mediated by changes in social and economic conditions.	**EPA**
	Understand impacts on road traffic injuries, physical activity, and noise exposure.	**EPA**

Summary of Chapter 6

Research on community-scale human effects will incorporate economic and social impact research methods to address how UOG activities influence community infrastructure and the provision of services, the impacts on local and regional governments, and how changes in economic activity affect existing industries and overall community quality of life. The research that integrates across health and community scale impact categories aims to promote understanding on how demographic change affects indirect health effects, and how changes in the built environment influence and contribute to nuisance exposure and community well-being.

In general, these research approaches and tools include targeted assessments for UOG-related exposures to be coupled with strategies to understand health effects including dose response assessments, epidemiologic studies, medical testing, biomarkers of exposure and disease, and toxicology studies of substances or exposures of concern. The information from these areas of research is critical to assess the potential human effects resulting from UOG production activities.

Ongoing interactions among the three Agencies will be needed to coordinate the research being performed on the other components of this effort, specifically that of the water quantity and quality, air quality, and ecological effects research areas. This coordination will gather data, information, and resource sharing, and help support and guide the direction of the human effects research thus increasing our understanding of the impacts of UOG activities. Broader scale coordination and collaboration with the UOG research efforts being performed by other agencies such as CDC/NCEH/ATSDR, CDC/ NIOSH, NIH/NIEHS, and all of HHS will also allow for a more comprehensive understanding of the potential human and environmental impacts associated with UOG production activities.

Topic 6: Ecological Effects

Introduction

This research topic focuses on identifying and monitoring current and potential ecological impacts associated with UOG production activities. Among other topics, the purpose of this Research Framework is to develop and coordinate research activities among the DOE, DOI, and EPA to provide the scientific understanding of ecological changes caused by UOG activities.

UOG exploration and development may have large-scale and lasting impacts on terrestrial and aquatic species, habitats, and ecosystems. This research will build on results described in other parts of this Research Framework to address the impacts of cumulative changes in land use, water availability, water and air quality, invasive and non-native species, and noise and light pollution on priority species and their habitats. The Framework will also focus on designated uses, ecosystem services of aquatic and terrestrial systems, migratory birds, threatened and endangered species, and fish and wildlife habitat. Results will allow prioritization of management actions to protect and restore valued ecological resources and guide the development of BMP to minimize and mitigate these effects using an adaptive management approach.

Key Science Questions

1) How are ecological resources (including migratory birds, threatened and endangered species, fish and wildlife habitat, designated uses, and ecosystem services) most likely to be impacted by changes in land use, water availability, water and air quality, invasive and non-native species, and light and noise over the UOG production life cycle? Where and when are impacts most likely to occur? At what spatial scales are impacts expected?
2) Which ecological resources are most vulnerable? How does the degree of change in land use, hydrology, water and air quality, and noise and light relate to changes in ecological resources?
3) How are these impacts different from or similar to those from other human activities such as conventional oil and gas production, renewable energy production, and urbanization?
4) What practices or actions would minimize risks or maximize benefits to ecological resources?
5) What new technologies, practices, or actions can be taken to restore or mitigate loss of ecological resources due to UOG production?

Current State of Knowledge

There is little peer-reviewed published literature that directly addresses the impacts of UOG on ecological resources. An initial search using the online Web of Science peer-reviewed literature database yielded 22 relevant articles. A majority of the articles were recently written being published in the last two years and addressed impacts on the loss of habitat, threatened and endangered species (T&E), etc. (Figure 12, right graph). The organism populations (taxa) identified in the studies included vegetation, mammals, microbes, etc. (Figure 12, left graph). More articles studied ecological effects in the southern (including Texas) and western United States, compared to the eastern United States. Although this is a cursory summary, it does suggest that little peer-reviewed research currently exists to directly assess ecological impacts of UOG activities.

The scientific community has, however, responded to this lack of information with several recent workshops on ecological impacts of UOG development (sponsors included the Society for Freshwater Science and the Ecological Society of America). There are also upcoming special issues in scientific journals dedicated to this topic (Environmental Practice, estimated publication date December 2012; New Solutions, estimated publication date June 2013 are examples). In addition, there is significant published literature on some of the primary stressors associated with UOG development. Highlights of these results are summarized below.

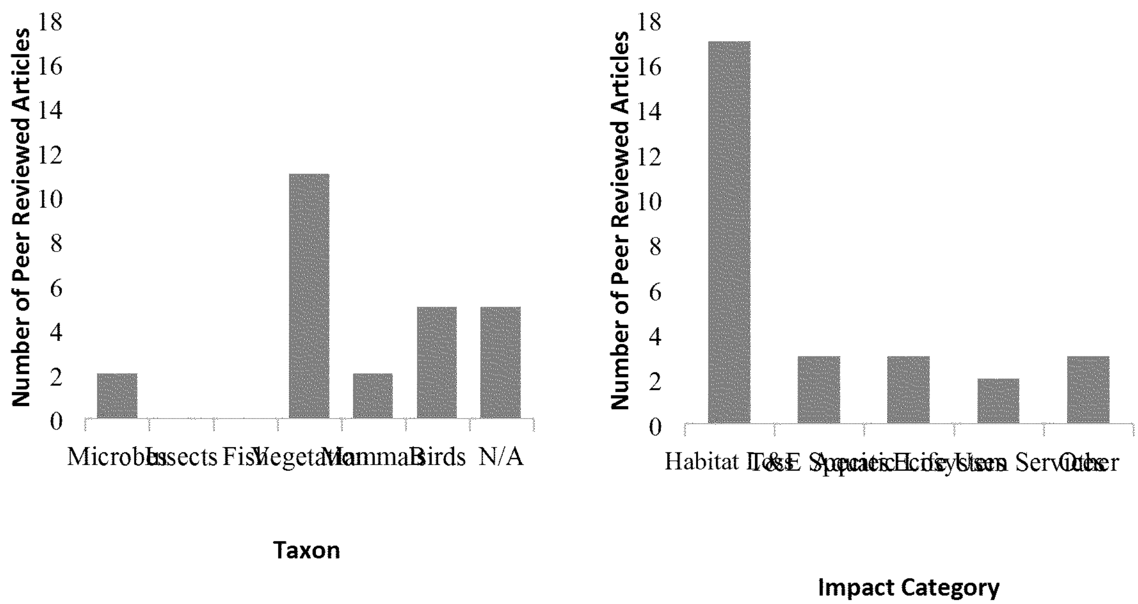


Figure 12: Results from Science Literature Search on Ecological Effects of UOG Development

Land Use Change

Landscape changes, such as loss or fragmentation of habitat, creation of edge or early successional habitat, changes in soil physical or chemical properties, or altered hydrologic flow paths in soils can impact terrestrial and aquatic resources. Habitat loss and fragmentation affect the density and dispersal of biota, such as migratory and breeding birds, amphibians, and insects, through direct loss, reduced patch size, increased edge effects, and decreased proximity of patches (Robinson et al., 1995; Trzcinski et al., 1999). Habitat fragmentation also can result in increased mortality or emigration of individuals moving among patches leading to lower re-colonization rates and smaller local populations (Fahrig and Merriam, 1994; Fahrig and Paloheimo, 1988) which are more susceptible to inbreeding, genetic drift, and bottlenecks that lower genetic diversity and potentially increase extinction risk, especially in threatened or endangered species (Ellstrand and Elam, 1993; Honnay et al., 2005; Alexander et al., 2011). Sensitivity of species depends on habitat association (e.g., terrestrial- versus wetland-breeding species), dispersal capability, life history, and other factors that vary among species in a community (Gibbs, 1998).

UOG exploration and extraction activities can alter soil physical and chemical characteristics and hydrologic flow paths in soils. For example, construction sites have higher soil bulk densities than forested areas (Alberty et al., 1984), which may decrease infiltration rates. Unpaved roads elevate runoff and sedimentation rates (Ziegler et al., 2000) and can affect downstream systems by changing the timing and volume of streamflow, water chemistry and sediment loads, and channel morphology (Megahan, 1984). Together, these land use changes may affect the natural flow regime of downstream systems and impact resident species.

Water Availability

The large volumes of water used for drilling, completion of gas wells, and hydraulic fracturing may alter freshwater availability and the environmental flow regimes necessary to sustain terrestrial and aquatic ecosystems and the species they support. Because hydrology is considered the "master variable" that drives many in-stream processes, including population persistence and community structure (Poff et al., 1997), flow alterations often contribute to the degradation of aquatic life, fish and wildlife habitat, and associated ecosystem services, as well as invasion by non-native species (Arthington et al., 2010; U.S. EPA, 2010a). Small headwater streams that drain areas where many wells are being drilled are particularly vulnerable to altered in-stream flows, either through direct water withdrawal or indirect changes to the landscape (soil hydrology). Key species and taxa of concern include aquatic macroinvertebrates, headwater fish and salamanders, vernal pool salamanders, terrestrial salamanders, freshwater mussels, migratory birds, bats, and rare, threatened, and endangered plants.

Water Quality

Aquatic and terrestrial biota may be impacted by water quality changes resulting from UOG development. Damage can result from both intended activities and from on-site accidents. Both point and non-point source pollution risks (e.g., salts, increased sedimentation, petroleum products and released drilling fluids) can have detrimental impacts on both aquatic and terrestrial communities. For instance, intentional and permitted application of hydraulic-fracturing fluids to a mixed hardwood forest in West Virginia resulted in severe damage to ground vegetation and mortality of 56 percent of the overstory trees within two years (Adams, 2011). Moreover, freshwater biota including macroinvertebrates, salamanders, algae, fish, and mussels are highly sensitive to increased salinity (e.g., Blasius and Merritt, 2002; Vosylienė et al., 2006; Karraker and Ruthig, 2008; U.S. EPA, 2010b) and sedimentation (e.g., Chutter, 1969; Ryan, 1991; U.S. EPA, 2010c). Other chemical constituents of UOG wastewater, such as heavy metals, hydrocarbons, barium, and radioisotopes may be toxic to specific organisms, or may bioaccumulate to the point where they are toxic. Other potential impacts linked to water quality changes beyond obvious toxicity issues include possible increased biological and chemical oxygen demand that may consume oxygen and other electron acceptors as well as alterations of the natural native microbial populations.

Air Quality

As discussed in Chapter 5, emissions associated with UOG include particulate matter, nitrogen oxides (NO_x), volatile organic compounds, carbon dioxide and methane, all of which can contribute to formation of ozone and contribute to GHG emissions. Investigation of GHG effects on ecosystems is outside the scope of the current effort.

Of the other compounds, the effects of ground level ozone and nitrogen oxides on ecosystems have been extensively studied. Ground-level ozone is well known to be capable of causing harmful effects on sensitive vegetation and ecosystems (U.S. EPA, 2006). Ozone can interfere with the ability of sensitive plants to produce and store food, leading to reduced growth and biomass production, and can visibly damage the leaves of sensitive trees and other plants (Figure 13).

Figure 13: Ozone Damage on Tulip Popular (U. S. Forest Service)

In addition to these immediate effects, continued ozone exposure over time can lead to increased susceptibility of sensitive plant species to disease, damage from insects, effects of other pollutants, competition, and harm from severe weather. Plant species that are sensitive to ozone and potentially are at an increased risk from exposure include trees such as black cherry, quaking aspen, ponderosa pine and cottonwood. Collectively, prolonged ozone exposure can lead to impacts on ecosystem services, including decreased productivity, loss of species diversity, changes in habitat quality, and changes in water and nutrient cycles.

Aside from being a precursor pollutant for ground level ozone formation, NOx can also cause harmful effects in a variety of ecosystems (U.S. EPA, 2008). Some of the main effects of NOx deposition include acidification and nutrient enrichment in both aquatic and terrestrial ecosystems. Acidification can cause a cascade of effects that harm susceptible aquatic and terrestrial ecosystems, including slower growth and injury to forests and localized extinction of fishes and other aquatic species. Excess nutrients resulting from NO_x deposition may result in increased primary productivity in nitrogen-limited ecosystems, biodiversity losses, changes in carbon cycling, and eutrophication and harmful algal blooms in freshwater, estuarine, and ocean ecosystems. Collectively, these effects can alter a variety of ecosystem services across the landscape (Compton et al., 2011).

Invasive and Non-Native Species

UOG development-associated infrastructure (e.g., transportation corridors), operation of gas wells, and water transport may hasten the appearance of invasive species, with potential impacts on fish and wildlife species and their associated habitat. For example, Prasad et al. (2010) showed that human transport is a more important vector for emerald ash borer (*Agrilus planipennis* Fairmaire) than insect flight in Ohio. Additional terrestrial invasives include garlic mustard (*Alliaria petiolata*), tree of heaven (*Ailanthus altissima*), brown marmorated stink bug (*Halyomorpha halys)*, and hemlock wooly adelgid (*Adelges tsugae).* Aquatic invasives transported by humans include the "rock snot" diatom known as Didymo (*Didymosphenia eminate*), the golden algae *Prymnesium parvum*, Asian tiger mosquito (*Aedes albopictus*), and rusty crayfish (*Orconectes rusticus*).

Noise Pollution

Noise pollution during UOG exploration and development and from the operation of established gas-well pad facilities may affect biological systems. Noise pollution will increase as a result of the construction of roads, pads and pipelines, increased vehicular traffic and road use to move equipment, aggregate, and water, and onsite compressors. Some of these effects are relatively short-lived, e.g., during the construction period, while others, such as the noise from compressors, continue for the productive life of a complex of pads and wells. Noise pollution does not necessarily have to be excessively loud to have negative effects on wildlife inasmuch as very low frequency sounds, including infrasound, could affect wildlife. Traffic-related and other noise has been suggested to decrease the occurrence, breeding density, and breeding success of birds (Brotons and Herrando, 2001), as well as have significant negative impacts on bird behavior and avian health (Lohr et al., 2003; Lengagne, 2008; Barber et al., 2010), putting species at risk by impairing signaling and listening capabilities necessary for successful communication and survival.

While some bird species can acclimate to noisy environments by adjusting the frequency range of their songs (Francis et al., 2011; Dowling et al., 2012), others may retreat from noise sources, further increasing the loss of effective habitat due to resource development, or experience reduced pairing success or other adverse effects (Habib et al., 2007). Some research suggests that competitive relationships among species may be altered by environmental noise. If a predatory species is more averse to the noise than a potential prey species, the noisy area may become a source habitat for the prey species. Foraging behavior may also be impacted by noise; for instance, "passive listening" bats avoid foraging areas with strong noise impact (Schaub et al., 2008).

Light Pollution

Night light pollution from gas-well pads, flaring of wells, roads, and other infrastructure could affect wildlife. Light pollution could affect species' physiology and behavior (Wise, 2007) as well as the celestial navigation of birds (Deda et al., 2007). For instance, chronic light pollution may entirely disrupt a plant's flowering and developmental patterns (Deda et al., 2007). Lighting of shale gas well pads also could pose hazards for migrating birds (and other dispersing animals) which may be attracted to and confused by lights on buildings, drilling rigs, and other human structures. This is both a site-specific and landscape change, as the proportion of the landscape free from artificial light sources is decreased by UOG development. Studies suggest that the navigation of birds using the horizon as orientation for direction is disrupted by lighting and sky glow (Rich and Longcore, 2006). Other research reveals that many nocturnally migrating birds die or lose a large amount of their energy reserves during migration as a result of encountering artificial light sources, possibly because artificial light interferes with the bird's magnetic compass, which is one of several orientation mechanisms especially important during overcast nights (Poot et al., 2008). This may be exacerbated during certain weather conditions (Avery et al., 1977).

Additionally, light pollution increases ambient illumination, disrupts photoperiod (i.e., the duration of an organism's daily exposure to light),and changes spectral properties of night light that may affect the physiology, behavior, and ecology of frog (Buchanan, 2006) and salamander populations (Wise and Buchanan, 2006) which may exacerbate declines of amphibian populations (Wise, 2007). American eel (*Anguilla rostrata*) migratory behavior could also be altered by light pollution, as they exhibit a strong negative phototaxis to light sources (i.e., movement in response to light stimulation). Light is a controlling variable for many in-stream processes as well, including primary production (Bott et al., 1997), insect drift (Bishop, 1969), foraging (Elliot, 1968), zooplankton diel vertical movement, and behavior of fish predators (Nicieza and Metcalfe, 1997). Many adult aquatic insects are attracted to lights, which are used to sample aquatic insect communities (Kovats et al., 1996) and are known to alter the composition of terrestrial invertebrate assemblages (Davies et al., 2012), but little is known about the effects of artificial lighting on the dispersal, reproductive success, or survival of aquatic insects (Perkin et al., 2011).

Research Needs: Topic 6 (Ecological Effects)

Table 15: Research Needs - Ecological Effects

Line of	Research Need	Participating Agencies (lead in bold)
Review and Synthesis	***Information and Gap Analysis***: Systematically review and synthesize literature, data sources, and monitoring protocols relevant to evaluating impacts of UOG on habitats, ecosystem services, aquatic life uses, migratory birds, and threatened and endangered species; develop web site for data sharing.	DOI, **EPA**
	Cumulative Impact Models: Estimate total cumulative impact of the full life cycle of UOG exploration, development, and delivery on natural resource systems of concern.	DOI, **EPA**
	Identify available data sources that could be used to establish pre-development ecological conditions for baseline conditions in areas of ongoing and future UOG	DOI, **EPA**

	activities.	
Water Quality	***Wastewater Toxicity Testing***: Expand toxicity database with additional chemicals and species of concern; determine the toxicity of chemicals and salts used or produced during UOG activities on aquatic life; and test alternate chemicals and emerging technologies for potential environmental risks and benefits.	DOI, **EPA**
	Identify sensitive aquatic communities, ecosystem services, and beneficial uses; develop monitoring protocols; and develop site-specific criteria based on spatial scales and biological organization.	DOI, **EPA**
	Develop a water monitoring network around UOG sites to assess biotic exposure to chemicals and evaluate the effectiveness of different chemical containment BMPs.	DOI, **EPA**
	Determine if sediment from UOG development poses a different threat to aquatic life than other activities such as agriculture and urbanization.	DOI, **EPA**
	Evaluate and, if appropriate, recommend changes to current BMPs to minimize the environmental impacts on aquatic ecosystems resulting from UOG development in an adaptive management framework.	**DOI**, EPA
Land Use	***Vulnerability Assessments***: Identify and prioritize key geographic regions, ecosystems and their services, sensitive aquatic communities, and critical wildlife habitats that have the greatest potential for impact from ongoing and potential UOG activities.	**DOI**, EPA
	Determine the most appropriate indicator species and biologically relevant markers for early detection of UOG impacts at different spatial and temporal scales.	DOI, **EPA**
	Produce ecological effects models to estimate total cumulative impact of the full life cycle of UOG exploration, development, and delivery on natural resource systems of concern.	**DOI**, EPA
	Develop models to predict species or community responses to disturbances from UOG operations.	DOI, **EPA**
	Develop statistically robust monitoring programs to quantify changes in key demographics of species, communities, and landscapes in areas of projected UOG development.	**DOI**, EPA
	Evaluate and, if appropriate, recommend changes to current BMPs to minimize the environmental impacts resulting from UOG development in an adaptive management framework.	**DOI**, EPA
Restoration	Determine the effectiveness of various restoration strategies in mitigating site specific and landscape level effects of UOG development.	**DOI**, EPA

Air Quality	Determine the concentration of potential air pollutants associated with UOG activities that would be harmful to threatened and endangered (T&E) and other species of concern.	**DOE**, DOI, EPA
	Determine if concentrations of gases and airborne particulates reach potentially harmful levels to wildlife in the vicinity of UOG operations.	**DOE**, DOI, EPA
	Determine total wildlife exposure and behavioral response to gasses and airborne particulates in the vicinity of UOG operations.	**DOE**, DOI, EPA
Water Availability	Determine impact of water withdrawal on aquatic resources of wetlands, headwater streams, and other low flow waterways such as ephemeral wetlands and vernal pools.	**DOI**, EPA
	Determine ecological flow requirements for aquatic species of concern potentially affected by low water from UOG operations.	**DOI**, EPA
Noise and Light	Determine if levels of noise and light reach potentially disturbing levels to T&E species and behavioral responses of those species light and noise generated by UOG operations.	**DOI**, EPA
Invasive Species	Determine the risk and pathways for introduction of invasive species due to multiple stressors to native plants and animals in and around UOG sites and transportation corridors.	**DOI**, EPA
	Evaluate, and if appropriate, recommend changes to current BMPs to prevent introduction and spread of invasive species in and around UOG development sites and transportation corridors.	**DOI**, EPA

Summary of Topic 6

While the DOE, DOI, and EPA will conduct research to determine the cumulative impacts of UOG extraction as a whole, the Agencies will expand the body of knowledge relating to the critical pathways by which adverse ecological effects of UOG are produced, and identify the most effective management actions to protect and restore ecological resources. DOI and EPA will co-lead this area of research, with support from from DOE.

The core competencies of impact assessment, risk assessment, and adaptive management are necessary to identify, predict, and mitigate the ecological impacts from UOG development. For this reason, there is a need for close collaboration between the Agencies as current research efforts proceed and planned research moves into implementation. In addition, close interactions among the three Agencies will be needed in order to coordinate ecological effects research with other components of the Research Framework and to guide changes in direction as this research and that being done by others increases our comprehension of the impacts of UOG activities.

Topic 7: Induced Seismicity

Introduction

This topic focuses on understanding current and potential induced seismic risk associated with UOG production. This research addresses how hydraulic fracturing and wastewater disposal may induce potentially damaging earthquakes.. Expanding the knowledge base regarding induced seismicity will enable the development and use of predictive tools, hazard assessment methodologies, and best practice techniques or standards to reduce seismic risks. In June 2012, the National Research Council released a report, "Induced Seismicity Potential in Energy Technologies" (National Research Council, 2012). Much of the proposed work included in this section is based on the recommendations, including proposed agency-specific actions, found in that report.

Key Science Questions

The key questions to be addressed in connection with fluid injection and production projects are:

1) What factors differentiate injection activities that induce earthquakes from those that do not?
2) To what extent can the occurrence of earthquakes induced by deep fluid-injection and production operations be influenced by altering operational procedures in ways that do not compromise project objectives?
3) Can deep fluid-injection operations interact with regional tectonics to influence the occurrence of natural earthquakes by, for example, causing them to occur earlier than they might have otherwise? Similarly, can induced earthquakes trigger much larger tectonic earthquakes?
4) What distribution of earthquakes (frequency of occurrence as a function of magnitude) is likely to result from a specified injection operation?
5) In the long-term, is there a risk of inducing seismicity from the extraction of gas over a decadal time scale?
6) What is likely to be the magnitude of the largest induced earthquake from a specific injection operation?
7) What is the probability of ground motion from induced earthquakes reaching a damaging level at a particular site, and what would be the projected consequences (e.g., injury and/or structural damage)?

Current State of Knowledge

The first studies of human-induced earthquakes began in 1894, when earthquakes triggered by mining activities were felt in Johannesburg, South Africa (McDonald, 1982). Since then, many other types of induced and triggered earthquakes have been either hypothesized or recognized (Ellsworth, et al., 2012). Seismicity associated with petroleum extraction became apparent in the early 1920s, with water reservoir impoundment in the late 1930s, with high pressure fluid injection at depth in the mid-1960s, and with natural gas production in the late 1960s.

The strengths of seismic events are typically described using the Moment Magnitude scale , that measures the energy released during an earthquake.. The scale is logarithmic, meaning that a magnitude 5.0 earthquake is ten times larger than a magnitude 4.0. Each unit on the Moment Magnitude scale represents a release of energy about 30 times greater than the immediately preceding unit. Notable examples of recent great earthquakes include the 2004 Sumatra earthquake in the Indian Oceanthat had a magnitude of 9.1 and the 1964 Anchorage, Alaska, quake that registered magnitude 9.2. These events are among the most powerful quakes ever recorded. Most earthquakes below magnitude 3.0 are not felt by human observers but can be recorded by seismographs. Earthquakes with magnitudes below 5.0 cause shaking of indoor items and minor structural building damage, but rarely significant damage. Magnitudes above 5.0 can cause serious damage depending on local ground conditions and construction methods.

Causal factors attributed to induced seismicity include changes in the state of crustal stress, pore fluid pressure changes, fluid volume changes, and applied forces or loads–mechanisms that may be interdependent. Often, for a particular case, the analysis of several possible causal mechanisms has provided different perspectives for understanding the resulting earthquakes. In general, a case for earthquake triggering is plausible if the corresponding perturbation–such as deep fluid injection–can be shown to have shifted a fault toward failure at a time that can account for the onset of seismicity. Establishing cause-and-effect can be difficult, but is easier to ascertain where natural seismicity is low and a chance correlation in time and space between a possible trigger and a natural earthquake sequence is unlikely.

The following sections examine the current state of knowledge of key areas affecting induced seismicity.

Fluid Injection Effects

Earthquakes associated with fluid injection have the following characteristics (McGarr et al., 2002). First, the seismicity tends to be triggered along preexisting faults that are hydraulically connected with wastewater injection points. The earthquake activity is usually concentrated on the portion of the fault with the best hydraulic connection to the point of injection. Second, there is evidence of time dependence. Initially, seismicity tends to be concentrated near the injection point and to respond rapidly to changes in injection pressure or rate. As injection proceeds, the zone of influence increases, the upper limit of earthquake magnitudes increases, and the response to changes in input pressures becomes more sluggish and subtle. This response tends to lag changes in injection parameters. Seismicity close to the injection point usually stops shortly after the injection ceases, whereas farther from the injection well, earthquakes may continue for some time thereafter.

Case Studies of Earthquakes Induced by Fluid Injection

Earthquakes induced by fluid injection have been well documented. Several cases in particular have been investigated in depth, providing a foundation of knowledge. One of the earliest and most compelling examples of seismicity related to fluid injection occurred at the Rocky Mountain Arsenal Well near Denver, Colorado in the 1960s (Evans, 1966; Healy et al., 1968). There, hazardous wastes were being injected under high pressures at a depth of 3.7 km (2.3 miles) at the Rocky Mountain Arsenal. The injection pressures were of the order of 10 megapascals (MPa) equivalent to 1,450 psi, above the initial formation pressure of 27 MPa (3,916 psi). Soon after injection started, earthquakes began to be felt in the Denver area, a region that previously had experienced little or no historic earthquake activity. The seismicity was initially concentrated near the bottom of the injection well, but eventually spread along a linear zone for about 8.7 km (5.4 miles) from the injection well. Of particular interest, is that the largest earthquake, of magnitude 4.85 (Herrmann et al., 1981), occurred more than a year after injection had ceased. Hsieh and Bredehoft (1981) showed that increases in fluid pressure of only 3.2 MPa (464 psi) were sufficient to stimulate earthquake activity on favorably oriented faults.

In 1986, near Ashtabula, Ohio, wastewater was injected into a 1.8 km (1.1 miles) deep hole into the Paleozoic strata of the Appalachian Plateau. A magnitude 3.6 main shock occurred in 1987, one year after the onset of injection and more than 30 km (18.6 miles) from any other previously known earthquake. Accurate location of aftershock hypocenters showed that this sequence started where a previously unknown fault in the Precambrian basement was closest to the well, i.e., 0.7 km (0.4 miles) from the injection point, and migrated westward about 2 km (1.2 miles). The 35 accurately-determined hypocenters all align and delineate the inferred trace of the fault; none were detected at the injection point. This example shows that pre-existing structure can play a key role in the spatial distribution of triggered seismicity.

Following the observations at the Rocky Mountain Arsenal, the USGS (Raleigh et al., 1976) performed a partially controlled fluid injection experiment in Rangely, Colorado, where water injection for secondary recovery in an oil field was producing low-level seismicity (maximum magnitude 3.1). Injection was in a number of wells with depths of up to 2 km (1.2 miles). During the experiment, earthquakes could be turned off and on by varying the pore pressure about a critical value of 26 MPa (3,771 psi), applied to a natural formation pressure on the order of 17 MPa (2,466 psi).

Water injected for solution salt mining in Dale, New York, (Fletcher and Sykes, 1977) provides another example of a partially controlled experiment, in this case, with lower pressures at shallower depths. Earthquakes of magnitude 1.0 to 1.4 formed a cluster about 650 m (2132.5 feet) across near the bottom of a 426 m (1397.6 feet) injection well. The earthquake activity ceased abruptly when the wellhead pressure dropped below 5 MPa (725 psi).

Events Triggered by Hydraulic Fracturing/Shale Gas Recovery

Most known injection-induced earthquakes are associated with wastewater disposal activities and not linked directly to hydraulic fracturing (National Research Council, 2012). There are, however, two reported cases of felt events linked to hydraulic fracturing, one in Oklahoma and one in England.

In Oklahoma, cases of hydraulic fracturing causing felt earthquakes were from massive hydrofrac treatments, producing many events with magnitudes up to 1.9 and 2.8 (Luza and Lawson, 1990; Holland, 2011).

In England (Lancashire, UK), while Cuadrilla Resources Ltd. was hydraulically fracturing in the Bowland shale, seismic events were observed after two treatments in the Preese Hall well (De Pater and Baisch, 2011). Among more than 50 events reported by the British Geological Survey, two had magnitudes of 2.3 and 1.5. These events were reported to be two orders of magnitude stronger than microseismicity normally observed during hydraulic fracturing treatments.

Although injection of fluids for the purposes of hydraulic fracturing does affect pressure and volume, because it uses much less injected fluid at one location in a much shorter span than other activities such as wastewater disposal, it is less likely to induce seismicity. A recent report by the National Research Council found that "The process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events." (National Research Council, 2012). Therefore, attention is focused on earthquakes associated with the disposal, by deep injection, of the wastewater co-produced with natural gas following hydraulic fracturing treatments.

Increased U.S. Earthquake Rates Linked to Wastewater Disposal

To put this hazard in perspective, since the beginning of 2011, the central and eastern portions of the United States have experienced a number of moderately strong earthquakes in areas of historically low earthquake hazard. These include earthquakes of magnitude 4.7 in central Arkansas on February 27, 2011; magnitude 5.3 near Trinidad, Colorado on August 23, 2011; magnitude 5.8 in central Virginia also on August 23, 2011; magnitude 4.8 in southeastern Texas on October 20, 2011; magnitude 5.6 in central Oklahoma on November 6, 2011; magnitude 4.0 in Youngstown, Ohio, on December 31, 2011; and magnitude 4.8 in east Texas on May 17, 2012. Of these, only the central Virginia earthquake is unequivocally a natural tectonic earthquake. In all of the other cases, there is evidence indicating, or at least suggesting, that the earthquakes were induced by wastewater disposal or other oil- and gas-related activities. Research completed to date strongly supports the conclusion that the earthquakes in Arkansas, Colorado, and Ohio were induced by wastewater injection. Investigations into the nature of the Oklahoma and Texas earthquakes are in progress.

The disposal of wastewater from oil and gas production by injection into deep geologic formations is a process that is being used with increasing frequency. The occurrence of induced seismicity associated with wastewater disposal from natural gas production, in particular, has increased significantly since the development of technologies to facilitate production of gas from shale and tight sand formations. While, as described above, there appears to be little seismic hazard associated with the hydraulic fracturing process that prepares the shale for production, the disposal of flowback and produced water does appear to be linked to increased seismicity.

Evidence of water disposal-related events was observed by an earthquake sequence near the Dallas-Fort Worth airport in 2008 and 2009 (Frohlich et al., 2011). Over the course of eight months, several felt seismic events ranging from magnitude 2.5 to magnitude 3.3 were detected where no previous earthquake activity had been detected, at locations with a mean epicenter within 0.5 km (0.3 miles) of a 4.2 km (2.6 miles) deep saltwater disposal well. In addition, recent research by USGS seismologist Bill Ellsworth and colleagues has demonstrated that magnitude 3.0 and larger earthquakes have significantly increased in the U.S. mid-continent since 2000, from a long-term average of 21 such earthquakes per year between 1970 and 2000; to 31 per year during 2000-2008; to 151 per year since 2008. Most of this increase in seismicity has occurred in areas of increased geologic disposal of production-related fluids.

Research Needs: Topic 7 (Induced Seismicity)

Table 16: Research Needs - Induced Seismicity

Line of	Research Need	Participating Agencies (lead in bold)
Data Collection	Identify five to ten industrial sites where background and multi-year monitoring activities can be conducted; conduct background and long-term monitoring studies at the sites chosen for assessment.	DOE, **DOI**
	Monitor microseismic activity during hydraulic fracturing, production, and injection activities.	DOE, **DOI**
	Collect data on injection rates and pressure and their relationship to magnitudes and frequencies of events.	DOE, **DOI**
Hazard and Risk Assessment	Analyze background data for multiple sites; develop component models for induced seismicity (IS) systems; and develop systems models for probabilistic hazards assessment.	DOE, **DOI**
	Validate/calibrate these tools.	DOE, **DOI**
Physics-Based Model Development	Develop models for forecasting induced seismic events and validate models with lab experiments and field data. As predictive models are developed, they must be validated and calibrated with microseismic (<1 magnitude) field data to demonstrate effectiveness. Most field data are on the microseismic scale, models will need to be able to reproduce similar results to be validated.	**DOE**, DOI
	Extend models to forecasting higher-magnitude induced seismic events. Models are needed to be able to determine under what conditions higher-magnitude (>2) induced seismic events can be caused, and to be able to	**DOE**, DOI

	predict the number and magnitude of large-scale events due to water disposal processes. Predictive models are needed to assess the potential seismic impact of moving into a new area for development.	
Dynamic Gap Assessment	An annual meeting will be held to disseminate information/advancements in the area of induced seismicity over the past year. At these meetings, gaps will be assessed to help identify future research needs. This is particularly important in this R&D area as there are large uncertainties involved.	**DOE**, **DOI**, EPA (lead rotating between DOE and DOI)
Long-Term Production from Unconventional Resources	Use predictive models calibrated with long-term production data sets to assess the potential for production activities to induce seismic events. Being able to predict the changes in the crustal stress field over the long-term during production will help determine if existing faults could be activated (to cause felt seismic activity).	**DOE**, DOI
	Assess the areal extent of the affected region over time. Being able to predict the areal extent of the reservoir affected over the production history will help determine the extent of subsurface characterization needed to ensure that a large existing fault will not be contacted.	**DOE**, DOI
Develop Novel Monitoring Tools	Develop seismic monitoring tools that improve the ability to detect microseismic events from various locations. Improved tools will help reduce costs of monitoring for seismic events and allow for higher resolution monitoring and monitoring in areas currently inaccessible. Such monitoring can also provide early warning for large-scale (felt) seismic events.	**DOE**, DOI
	Conduct large scale 3-D geologic mapping and apply LIDAR and high-resolution geophysical techniques (particularly seismic reflection surveying) to detect existing geologic faults that could induce seismic events. If we can detect such faults before operations, we can potentially avoid such areas and reduce the risk of damaging earthquakes.	**DOE**, DOI

Summary of Topic 7

In general, induced seismicity research activities align with Agency core competencies, including data gathering, seismic detection, and hazard assessment at DOI and predictive tool development, data gathering, risk evaluation, and unconventional technology research at DOE. EPA, which together with State agencies, regulates Class II injection wells under the Safe Drinking Water Act, is a primary stakeholder in the information that will be developed as part of this research. Ongoing interactions among the three Agencies will be needed to coordinate induced seismicity research with research planned for other components of this Research Framework, and to guide changes in direction of this research as understanding of how UOG activities affect induced seismicity increases.

Next Steps

Data Quality Assurance/Quality Control

The DOE, DOI, and EPA will conduct research activities in a clear and open manner, using established techniques, and will subject results to peer review. All research envisioned by the Framework will be conducted, and results reported, with appropriate quality assurance/quality control (QA/QC) protocols.

Established QA/QC methods for evaluating the effects of UOG development on humans and ecosystems will be used for monitoring and measuring environmental parameters. In some cases, due to the nature of research activities that apply or develop new techniques and methods for sampling, measurement, and data analysis, careful documentation of practices will be undertaken following recognized QA/QC techniques to ensure reproducibility of results.

To enable development of effective risk management strategies across research chapters, sources of existing data will be evaluated and, where necessary, additional measurements and assessments may be required in several geographic areas. A range of measurement methods will be used to identify those that provide the highest quality data in terms of precision, accuracy, and representativeness. Emerging measurement techniques will be applied, modified, and evaluated in collaboration with partners to advance the availability of low-cost field measurement technologies. Individual technologies may not be applicable for all purposes, but would be appropriate for different uses depending upon accuracy, detection levels, and related factors.

Data Publication and Sharing

Research teams assembled to address the UOG research activities developed through this document will communicate on a regular basis through electronic communications, teleconferences, webinars, and in-person meetings. For example, all supporting water resources data and information will be made available through existing publicly-accessible databases, and induced seismicity data sets generated by each agency can be distributed for the purposes of knowledge sharing, model validation, and calibration. The DOI is updating its policy for data cataloging so that information from different sources are made available in a consistent catalog. Data collected for individual sites will be published in peer-reviewed articles.

Outreach Mechanisms

The dynamic nature of this research requires that the state of understanding be evaluated periodically to enable the collaborating Agencies to refine and adjust multi-year research activities. These efforts will require active stakeholder engagement to facilitate and promote discussion of the state of the science, knowledge gaps, and research activities. As necessary, the Agencies will evaluate community-wide options to conduct these periodic evaluations collaboratively with industries, state agencies, and academia. For example, water quality research will proceed as a partnership with those federal and state agencies and river basin commissions responsible for water quality monitoring along with the various private sector environmental engineering companies engaged to conduct operations. To ensure coordination and communication of data across the multiple organizations and stakeholders involved in expanding understanding of the impacts of UOG activities, the three Agencies will organize an annual webinar and/or seminar to address the current state of knowledge.

Appendix A: Glossary of Terms

Aquifer	An underground formation or group of formations in rocks and soils containing enough ground water to supply wells and springs.
Conventional Reservoirs	Sands and carbonates (limestones and dolomiates) that contain the gas in interconnected pore spaces that allow flow to the wellbore. The gas in the pores can move from one pore to another through smaller pore-throats that create permeable flow through the reservoir. In conventional natural gas reservoirs, the gas is often sourced from organic-rich shales proximal to the more porous and permeable sandstone or carbonate.
Continuous Reservoir	A type of areally (a particular extent of space or surface) extensive reservoir that contains hydrocarbon throughout, rather than containing a water contact or being significantly affected by a water column or a defined structural closure.
Development	The phase of petroleum operations that occurs after exploration has proven successful, and before full-scale production.
Economically Recoverable Resources	A sub-set of the technically recoverable resources (TRR) that can be developed profitably given prevailing market conditions.
Ecosystem	Dynamic and interrelating complex of plant and animal communities and their associated nonliving (e.g. physical and chemical) environment.
Endangered	The classification provided to an animal or plant in danger of extinction within the foreseeable future throughout all or a significant portion of its range.
Exploration	The initial phase in petroleum operations that includes generation of a prospect or play or both, and drilling of an exploration well. Appraisal, development and production phases follow successful exploration.
Hydrocarbon	A naturally occurring organic compound comprising hydrogen and carbon. Hydrocarbons can be as simple as methane [CH_4], but many are highly complex molecules, and can occur as gases, liquids or solids. The most common hydrocarbons are natural gas, oil and coal.

Hydraulic Fracturing	A stimulation treatment routinely performed on oil and gas wells in low-permeability reservoirs. Specially engineered fluids (commonly made up of water and chemical additives) (commonly made up of water and chemical additives) are pumped at high pressure and rate into the reservoir interval to be treated, causing a vertical fracture to open. When the pressure exceeds the rock strength, the fluids open or enlarge fractures that can extend sever hundred feet away from the well. After the fractures are created, p propping agent is pumped into the fractures to keep them from closing when the pumping pressure is released. After fracturing is completed, the internal pressure of the geologic formation cause the injected fracturing fluids to rise to the surface where it may be stored in tanks of pits prior to disposal or recycling.
In-place Resources	Every molecule of gas thought to exist. This term is generally irrelevant to discussion of production potential (particularly with respect to unconventional resources) other than to provide a theoretical upper bound.
Permeability	The ability of a substance to allow another substance to pass through it, especially the ability of a porous rock, sentiment, or soil to transmit fluids through pores and cracks.
Play	An area, controlled by the same set of geological circumstances, in which hydrocarbon accumulations or prospects of a given type occur.
Produced water	A term used to describe water produced from a wellbore that is not a treatment fluid. The characteristics of produced water vary and use of the term often implies an inexact or unknown composition. It is generally accepted that water within the pores of shale reservoirs is not produced due to its low relative permeability and its mobility being lower than that of gas.
Production	The phase that occurs after successful exploration and development and during which hydrocarbons are drained from an oil or gas field.
Proppant	Sized particles mixed with fracturing fluid to hold fractures open after a hydraulic fracturing treatment. In addition to naturally occurring sand grains, man-made or specially engineered proppants, such as resin-coated sand or high-strength ceramic materials like sintered bauxite, may also be used.
Proved Reserves	That portion of recoverable resources that is demonstrated by actual production or conclusive formation tests to be technically, economically and legally producible under existing economic and operating conditions.

Reservoir Characterization	Geologic and engineering descriptions of the detailed nature and variability in reservoir conditions.
Reserves	Resources that have been be discovered, are recoverable, are commercially viable, and remaining (as of the evaluation date) based on the development project(s) applied. As one moves from undiscovered *resources* to *reserves* there is increasing geologic certainty and economic viability.
Resources	Both known and undiscovered oil and gas accumulations.
Resource Assessments	Estimates of ultimate areal extent and hydrocarbon production potential for key or representative accumulations, including those in development, those emerging, and those that are as yet undeveloped.
Seismicity	Relative frequency and distribution of earthquakes.
Shale	A fine-grained, fissile, detrital sedimentary rock formed by consolidation of clay- and silt-sized particles into thin, relatively impermeable layers. It is the most abundant sedimentary rock. Shale can include relatively large amounts of organic material compared with other rock types and thus has potential to become a rich hydrocarbon source rock, even though a typical shale contains just 1% organic matter. Its typical fine grain size and lack of permeability, a consequence of the alignment of its platy or flaky grains, allow shale to form a good cap rock for hydrocarbon traps.
Shale gas	Natural gas produced from shale formations.
Stimulation	A treatment performed to restore or enhance the productivity of a well. Stimulation treatments fall into two main groups, hydraulic fracturing and matrix treatments. Fracturing treatments are performed above the fracture pressure of the reservoir formation and create a highly conductive flow path between the reservoir and the wellbore. Matrix treatments are performed below the reservoir fracture pressure and generally are designed to restore the natural permeability of the reservoir following damage to the near-wellbore area. Stimulation in shale gas reservoirs typically takes the form of hydraulic fracturing treatments.
Technically Recoverable Resources	Volumes available for production using known technologies, but without specific regard to commerciality.

Tight	Relatively impermeable reservoir rock from which hydrocarbon production is difficult. Reservoirs can be tight because of smaller grains or matrix between larger grains, or they might be tight because they consist predominantly of silt- or clay-sized grains, as is the case for shale reservoirs.
Unconventional Reservoirs	Low permeability (tight) formations such as tight sands and carbonate, coal, and shale. In unconventional gas reservoirs, the gas is often sourced from the reservoir rock itself. Because of the low permeability of these formations, it is typically necessary to stimulate the reservoir to create additional permeability. Hydraulic fracturing of a reservoir is the preferred stimulation for gas shales.
Unconventional Resources	Those resources that cannot be produced economically through standard drilling and completion practices, such as shale gas, shale oil, tight gas, and tight oil.
Volatile Organic Compounds	Emitted as gases from certain solids or liquids, VOCs include substances—some of which may have short- and long-term adverse health effects—such as benzene, toluene, methylene chloride, and methyl chloroform.
Wellbore	A borehole, including the openhole or uncased portion of the well. Borehole may refer to the inside diameter of the wellbore wall, the rock face that bounds the drilled hole.

These definitions were drawn from the text of this Research Framework, and a number of glossaries found on web pages by EPA, the U.S. Fish and Wildlife Service, Schlumberger, and The Encyclopedia of Earth. See references listing in Appendix A.

Appendix B: References

Letter to the Public

- Jackson, Lisa P. U.S. Environmental Protection Agency. Administrator's Site. "Obama Administration Announces Members of Steering Team to Lead Interagency Coordination of Unconventional Oil and Gas Research and Development." Accessed October 10, 2012 http://blog.epa.gov/administrator/2012/05/24/obama-administration-announces-members-of-steering-team-to-lead-interagency-coordination-of-unconventional-oil-and-gas-research-and-development/.
- U.S. Department of Energy, U.S. Department of the Interior, and the U.S. Environmental Protection Agency. "Memorandum: Multi-Agency Collaboration on Unconventional Oil and Gas Research." (Washington, DC: April 13, 2012).
- U.S. Department of Energy. Secretary of Energy Advisory Board (SEAB). *Shale Gas Production Subcommittee Second Ninety Day Report. (*Washington, DC*:* November 18, 2011*)* Accessed from http://www.shalegas.energy.gov/resources/081811_90_day_report_final.pdf.
- U.S. Energy Information Administration. *Annual Energy Outlook 2012.* DOE/EIA-0383 (Washington, DC: June 2012*),* Accessed from http://www.eia.gov/forecasts/aeo/.
- The White House. *Blueprint for a Secure Energy Future*. (Washington, DC: March 31, 2011).
- The White House. "Executive Order: Supporting Safe and Responsible Development of Unconventional Domestic Natural Gas Resources." (Washington, DC: April 13, 2012).

Executive Summary

- U.S. Department of Energy, U.S. Department of the Interior, and the U.S. Environmental Protection Agency. "Memorandum: Multi-Agency Collaboration on Unconventional Oil and Gas Research." (Washington, DC: April 13, 2012).
- U.S. Department of Energy. Secretary of Energy Advisory Board (SEAB). *Shale Gas Production Subcommittee Second Ninety Day Report. (*Washington, DC*:* November 18, 2011*),* Accessed from http://www.shalegas.energy.gov/resources/081811_90_day_report_final.pdf.
- U.S. Environmental Protection Agency. *GHG Reporting Program 2010.* (Washington, DC: 2010).
- U.S. Energy Information Administration. *Annual Energy Outlook 2012.* DOE/EIA-0383 ,(Washington, DC: June 2012*),* Accessed from http://www.eia.gov/forecasts/aeo/.
- The White House. *Blueprint for a Secure Energy Future*. (Washington, DC: March 31, 2011).
- The White House. "Executive Order: Supporting Safe and Responsible Development of Unconventional Domestic Natural Gas Resources." (Washington, DC: April 13, 2012).

Chapter 1: Introduction

- U.S. Department of Energy. Office of Fossil Energy. *Modern Shale Gas Development in the United States: A Primer.* (National Energy Technology Laboratory: April 2009).
- U.S. Energy Information Administration. "Summary Maps: Natural Gas in the Lower 48 States and North America." Accessed August 14, 2012 from http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm
- U.S. Department of Energy, U.S. Department of the Interior, and the U.S. Environmental Protection Agency. "Memorandum: Multi-Agency Collaboration on Unconventional Oil and Gas Research." (Washington, DC: April 13, 2012).
- U.S. Department of Energy. Secretary of Energy Advisory Board (SEAB). *Shale Gas Production Subcommittee Second Ninety Day Report. (*Washington, DC: November 18, 2011*),* Accessed from http://www.shalegas.energy.gov/resources/081811_90_day_report_final.pdf.
- The White House. *Blueprint for a Secure Energy Future.* (Washington, DC: March 31, 2011).
- The White House. "Executive Order: Supporting Safe and Responsible Development of Unconventional Domestic Natural Gas Resources." (Washington, DC: April 13, 2012).

Chapter 2: Understanding the Scale and Nature of U.S. Unconventional Oil and Gas Resources

- Avila, J. "Devonian Shale as a Source of Gas." In *Natural Gas from Unconventional Geologic Sources*, U.S. ERDA Report FE-2271-I (1976), pp. 73-85.
- Bloomberg, Michael R., and Mitchell, George P. "Fracking is Too Important to Foul Up." *Washington Post*, (Washington DC: 2012), Accessed August 24, 2012 from http://www.washingtonpost.com/opinions/fracking-is-too-important-to-foul-up/2012/08/23/d320e6ee-ea0e-11e1-a80b-9f898562d010_story.html?tid=wp_ipad.
- Boswell, R. "Play UDs: Upper Devonian Black Shales." In: Roen, J., Walker, B., eds., *The Atlas of Major Appalachian Gas Plays. West Va. Geological and Economic Survey.* Publication v-25 (1996), p 93-99, Accessed from http://pubs.rsc.org/en/Content/ArticleLanding/2011/EE/C0EE00203H
- Brown, P. "Energy from Shale – A Little Used Natural Resource." *Natural Gas from Unconventional Geologic Sources.* US ERDA Report FE-2271-I (1976), p 86-99.
- Ley, H. A. "Natural Gas." In: *Ley, H.A, ed., Geology of Natural Gas,* American Association of Petroleum Geologists Symposium, (1935), pp. 1073-1149, Accessed at AAPG Datapages/Archives. http://archives.datapages.com/data/specpubs/fieldst1/data/a008/a008/0001/2300/2321.
- Kharaka, Y.K. and Hanor, J.S. "Deep Fluids in the Continents I: Sedimentary Basins." In: Drever, J.I., (ed.) *Surface and Ground Water, Weathering and Soils: Treatise on Geochemistry*, Vol. 5 (2007), pp. 1-48.
- Schenk, C.J., and Pollastro, R.M. "Natural Gas Production in the United States: U.S. Geological Survey Fact Sheet." FS-113-01, 2p. (2002), Accessed from http://pubs.usgs.gov/dds/dds-069/dds-069-b/Chapter_1.htm.
- U.S. Department of Energy. The Strategic Center for Natural Gas and Oil (SCNGO) *The DOE's Unconventional Gas Research Programs, 1976-1995: An Archive of Important Results*. National Energy Technology Laboratory. Natural Gas Program Archive (2007), 2 DVD set.
- U.S. Energy Information Administration. Figure 6: "U.S. Natural Gas Production History and Projections from 1980-2036." Accessed from http://www.eia.gov/energy_in_brief/about_shale_gas.cfm.

- U.S. Energy Information Administration. *Annual Energy Outlook 2012.* DOE/EIA-0383 (Washington, DC: June 2012*)*, Accessed from http://www.eia.gov/forecasts/aeo/.

Chapter 3: Water Quality

- U.S. Department of the Interior. Bureau of Reclamation (BOR). *Oil and Gas Produced Water Management and Beneficial Use in the Western United States.* Science and Technology Program Report No. 157 (September 2011).
- Entrekin, S., Evans-White, M., Johnston, B., and Hagenbuch, E. "Rapid Expansion of Natural Gas Development Poses a Threat to Surface Waters." *Frontiers in Ecology & Environment*, Vol 9 (2011), pp. 503-511.
- Heilweil, V. M., Stolp, B. J., Susong, D. D., Kimball, B. A., Rowland, R. C., Marston, T. M., and Gardner, P. M. "Stream Methane Tracer Test for Evaluating Groundwater Impacts Associated with Hydraulic Fracturing." *Geological Society of America Annual Meeting Abstracts (*Charlotte, North Carolina: November 2012).
- Molofsky, L. J., Connor, J.A., Farhat, S.K, Wylie, A.S. and Wagner, T. "Methane in Pennsylvania Groundwaters Unrelated to Marcellus Shale Hydraulic Fracturing." *Oil and Gas Journal*, 12/05/2011, Accessed from http://www.ogj.com/1/vol-109/issue-49/exploration-development/methane-in-pennsylvania-water-full.html.
- Osborn, S. G., A. Vengosh, N. R. Warner, and R. B. Jackson. "Methane Contamination of Drinking Water Accompanying Gas-Well Drilling and Hydraulic Fracturing." *Proceedings of the National Academy of Sciences.* PNAS 108, Vol. 20 (2011), pp. 8172-8176.
- Revesz, K. M., Breen, K. J., Baldassare, A. J., and Burruss, R. C. "Carbon and Hydrogen Isotopic Evidence for the Origin of Combustible Gases in Water-Supply Wells in North-Central Pennsylvania." *Applied Geochemistry,* Vol. 27. No. 1 (2012), pp. 361-375.
- Rozell, D. J and Reaven, S. J.. "Water Pollution Risk Associated with Natural Gas Extraction from the Marcellus Shale." *Risk Analysis,* Vol. 32, No. 8 (2012). pp. 1382-1393.
- Sanford, W. E., Haase, K.B., and Busenberg, E. "Dating Base Flow in Streams Using Dissolved Gases and SF_6. " *Geological Society of America Annual Meeting Abstracts*, (Charlotte, NC: November 2012).
- Solomon, D.K., Plummer, L.N., Busenberg, E., Cook, P.G. "Chapter 7: Practical applications of CFCs in hydrological investigations," *in Use of Chlorofluorocarbons in Hydrology : A Guidebook.* (Vienna : International Atomic Energy Agency: 2006).
- Stolp, B. J, Solomon, D. K. , Suckow, A., Vitvar, T., Rank, D., Aggarwal, P.K., and Han, L.F. "Age Dating Base Flow at Springs and Gaining Streams using Helium-3 and Tritium: Fischa-Dagnitz System, Southern Vienna Basin, Austria." *Water Resource Research Journal* , Vol, 46, W07503 (2010), doi:10.1029/2009WR008006.
- U.S. Environmental Protection Agency. "Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources." The EPA/600/R-11/122 (2011), p. 174.
- Warner, N. R., Jackson, R. B., Darrah T. H., Osborn, S. G., Down A., Zhao, K., White, A., and Vengosh, A. "Geochemical Evidence for Possible Natural Migration of Marcellus Formation bBine to Shallow Aquifers in Pennsylvania." *Proceedings of the National Academy of Science,* PNAS, Vol. 109, No. 30 (2012), pp. 11961-11966.

Chapter 4: Water Availability

- Government Accountability Office. *Energy-Water Nexus: Information on the Quantity, Quality, and Management of Water Produced During Oil and Gas Production.* Report GAO-12-156, (Washington, DC: 2012), p. 51.

- Groat, C.G. and Grimshaw.,T.W. *Fact-Based Regulation for Environmental Protection in Shale Gas Development.* The Energy Institute, (The University of Texas at Austin, Austin, TX: 2012), p. 414, http://energy.utexas.edu/.
- Nicot, J.P., and Scanlon, B.R. "Water Use for Shale Gas Production in Texas. "*U.S. Environmental Science and Technology*, dx.doi.org/10.1021/es204602t, Vol. 46 (2012), pp. 3580−3586.
- Soeder, D. J. and Kappel, W.M. "Water Resources and Natural Gas Production from the Marcellus Shale." *USGS Fact Sheet 2009–3032*, (U.S. Geological Survey, Reston, VA:2009), p. 6. http://pubs.usgs.gov/fs/2009/3032/.

Chapter 5: Air Quality and Greenhouse Gas Emissions

- Alvarez, R. A., Pacala, S.W., Winebrake, J.J., Chameides, W.I. and Hamburg. S. P. "Greater Focus Needed on Methane Leakage From Natural Gas Infrastructure." *Proceedings of the National Academy of Sciences,* (Washington, D.C: April 9, 2012).
- Cathles, L. M. "Assessing the Greenhouse Impact of Natural Gas." *Geochemistry, Geophysics, and Geophysics (G3), Vol 13* (2012), Q06013.
- Colorado Department of Public Health and Environment. *Public Health Implications of Ambient Air Exposures as Measured in Rural and Urban Oil & Gas Development Areas – An Analysis of 2008 Air Sampling Data: Garfield County, Colorado. (*Prepared under a Cooperative Agreement with the U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry, Division of Health Assessment and Consultation, Atlanta, Georgia: August 26, 2010)
- Colorado Department of Public Health and Environment and Agency for Toxic Substances and Disease Registry. *Public Health Implications of Ambient Air Exposures to Volatile Organic Compounds as Measured in Rural, Urban, and Oil & Gas Development Areas.* Garfield County, (Colorado, Colorado Department of Public Health and Environment: 2008), p. 67.
- Eastern Research Group and Sage Environmental Consulting. *City of Fort Worth Natural Gas Air Quality Study, (*Eastern Research Group and Sage Environmental Consulting:, 2011), p. 320.
- Ethridge, S. "Memorandum: Health Effects Evaluation of Region 4 Carbonyl Monitoring Project, November 6 – 10, 2010, Sampling for Carbonyl Compounds in Dish and Fort Worth, Texas. " (Texas Commission on Environmental Quality, Austin, Texas: 2011), p. 39.
- Howarth, R., Santoro, R. and Ingraffea, A. "Methane and the Greenhouse-Gas Footprint of Natural Gas from Shale Formations – A Letter." *Climatic Change,* (2011), pp. 1-12.
- Lazor, N. "Southwestern Pennsylvania Marcellus Shale Short-Term Ambient Air Sampling Report." Pennsylvania Department of Environmental Protection (2010).
- McKenzie, L. M., R. Z. Witter, L.S. Newman, and J.L. Adgate. "Human Health Risk Assessment of Air Emissions from Development of Unconventional Natural Gas Resources." *Science of the Total Environment,* Vol. *424* (May 1, 2012), pp. 79-87.
- Modrak, M. T., Amin, M.S. et al. "Understanding Direct Emission Measurement Approaches for Upstream Oil and Gas Production Operations." *Air & Waste Management Association 105th Annual Conference & Exhibition, (*San Antonio, TX, Air & Waste Management Association, 2012), p. 10.
- Pétron, G., Frost, G., Miller, B.R., Hirsch, A.J., Montzka, A.K., Trainer, M., Sweeny, C., Andrews, A.E., Miller, L., Kofler, J., Bar-Ilan, A., Dlugokensky, E.J., Patrick, L., Moore Jr., C.T., Ryerson,

T.B., Siso, C., Kolodezy, W., Lang, P.M, Conway, T., Novelli, P., Masarie, K., Hall, B., Guenther, D., Kitzis, D., Miller, J., Welsh, D., Wolfe, D., Neff, W., and Tans, P. "Hydrocarbon Emissions Characterization in the Colorado Front Range: A Pilot Study." *Journal of Geophysical Research*, Vol. 117, No. D4 (2012), p. D04304.

- Skone, T. Littlefield, J.J. and Marriott, J. *Life Cycle Greenhouse Gas Inventory of Natural Gas Extraction, Delivery and Electricity Production*. (National Energy Technology Laboratory, U.S. Department of Energy: 2011).
- Thoma, E. D., Squier, W.C. et al. *Assessment of Methane and VOC Emissions from Select Upstream Oil and Gas Production Operations Using Remote Measurements: Interim Report on Recent Survey Studies.* Air & Waste Management Association 105th Annual Conference & Exhibition, (San Antonio, TX, Air & Waste Management Association, 2012), p. 15.
- U.S. Environmental Protection Agency. (2010). "Mandatory Reporting of Greenhouse Gases: Petroleum and Natural Gas Systems; Final Rule." *Federal Register* , Vol. 75, No. 229, pp. 74458-74515.
- U.S. Environmental Protection Agency. (2012a). *Oil and Natural Gas Sector: New Source Performance Standards and National Emission Standards for Hazardous Air Pollutants Reviews.* Office of Air and Radiation. (Washington, DC, 2012), p. 588.
- Weber, C. L. and C. Clavin. "Life Cycle Carbon Footprint of Shale Gas: Review of Evidence and Implications." *Environmental Science & Technology*, Vol. 46, No. 11, (2012), pp. 5688-5695.
- Zielinska, B., E. M. Fujita, Campbell, D, Samburova, V. Hendler, E, and Beskid, C.S. “Monitoring of Emissions from Barnett Shale Natural Gas Production Facilities for Population Exposure Assessment.” American Geophysical Union, Fall Meeting 2010 (December 2010), p. 71.

Chapter 6: Effects on People and their Communities

- Boxall, P.C., W.H. Chan, and M.L. McMillan. “The Impact of Oil and Natural Gas Facilities on Rural Residential Property Values: A Spatial Hedonic Analysis.” *Resource and Energy Economics*, Vol. 27, No. 3 (2005), pp. 248–269.
- Marchand, J. “Local Labor Market Impacts of Energy Boom-Bust-Boom in Western Canada.” *Journal of Urban Economics,* Vol. 71. No. 1 (2012), pp 165–174.
- National Research Council. (2011). National Research Council. *Sustainability and the US EPA*. (The National Academies Press, Washington, DC: 2011).
- Weber, J.G. “The Effects of a Natural Gas Boom on Employment and Income in Colorado, Texas, and Wyoming.” *Energy Economics*, Vol. 34, No. 5 (2012), pp. 1580–1588.

Chapter 7: Ecological Effects

- Adams, M.B. “Land Application of Hydrofracturing Fluids Damages a Deciduous Forest Stand in West Virginia.” *Journal of Environmental Quality*, Vol. 40 (2011), pp. 1340-1344.
- Alberty, C.A., Pellett, H.M., and Taylor, D.H. “Characterization of Soil Compaction at Construction Sites and Woody Plant Response.” *Journal of Environmental Horticulture*, Vol. 2, (1984), pp. 48-53.
- Alexander, L.C., Hawthorne, D.J., Palmer, M.A.., and Lamp, W.O. “Loss of Genetic Diversity in the North American mayfly *Ephemerella invaria* Associated with Deforestation of Headwater Streams.” *Freshwater Biology*, Vol. 56 (2011), pp. 1456-1467.
- Arthington, A.H., Naiman, R.J., McClain, M.E., and Nilsson, C. (2010). “Preserving the Biodiversity and Ecological Services of Rivers: New Challenges and Research Opportunities.”

Freshwater Biology, Vol. 55 (2010), pp. 1-16.

- Avery, M., Springer, P.F., and Cassel, J.F. "Weather Influences on Nocturnal Bird Mortality at a North Dakota Tower. " *Wilson Bulletin*, Vol. 89 (1977), pp. 291–299.
- Barber, J.R., Crooks, K.R., and Fristrup. K. "The Costs of Chronic Noise Exposure for Terrestrial Organisms." *Trends Ecology and Evolution*, Vol. 25 (2010), pp. 180–189.
- Blasius, B. J., and Merritt, R. W. "Field and Laboratory Investigations on the Effects of Road Salt (NaCl) on Stream Macroinvertebrate Communities." *Environmental Pollution,* Vol.120 (2002), pp. 219-231.
- Bishop, J.E. "Light Control of Aquatic Insect Activity and Drift." *Ecology* Vol. 50 (1969), pp. 371-380.
- Bott, T.L., Brock, J.T., Baattrup-Pedersen, A., Chambers, P.A., Dodds, W.K., Himbeault, K.T., Lawrence, J.R., Planas, D., Snyder, E., and Wolfaardt, G.M. "An Evaluation of Techniques for Measuring Phytoplankton Metabolism." In: Chambers. *Canadian Journal of Fisheries and Aquatic Sciences,* Vol. 54 (1997), pp. 715-725.
- Brotons L., and Herrando, S. "Reduced Bird Occurrence in Pine Forest Fragments Associated with Road Proximity in a Mediterranean Agricultural Area." *Landscape and Urban Planning*, Vol. 57 (2001), pp. 77-89.
- Buchanan, B.W. "Observed and Potential Effects of Artificial Night Lighting on Anuran Amphibians." In: Rich, C., and Longcore, T., eds. *Ecological Consequences of Artificial Night Lighting.* (Washington, DC: Island Press, 2006), pp. 192-220.
- Chutter, F.M. "The Effects of Silt and Sand on the Invertebrate Fauna of Streams and Rivers." *Hydrobiologia*, Vol. 34 (1969), pp. 57-76.
- Compton, J.E., Harrison, J.A., Dennis, R.L., Greaver, T.L., Hill, B.H., Jordan, S.J., Walker, H., and Campbell, H.V. "Ecosystem Services Altered by Human Changes in the Nitrogen Cycle: A New Perspective for US Decision Making." *Ecology Letters*, Vol. 14 (2011), pp. 804-815.
- Davies T.W., Bennie, J., and Gaston, K.J. "Street Lighting Changes the Composition of Invertebrate Communities." *Biology Letters,* Vol. 8, No. 5, (October 23, 2012), pp. 764-767. Published online before print (May 23, 2012), doi: 10.1098/rsbl.2012.0216.
- Deda, P., Elbertzhagen, I., and Klussmann, M. "Light Pollution and the Impacts on Biodiversity, Species and Their Habitats." In: C. Marín and J. Jafari (eds.) *Starlight – A Common Heritage*. International Conference in Defense of the Quality of the Night Sky and the Right to Observe the Stars. Starlight Initiative, Instituto de Astrofísica de Canarias (IAC), La Palma, Canary Islands, Spain, April 19-20, 2007.
- Dowling, J.L., Luther, D.A., and Marra, P.P. "Comparative Effects of Urban Development and Anthropogenic Noise on Bird Songs." *Behavioral Ecology*, Vol. 23 (2012), pp. 201-209.
- Elliot, J.M. "Daily Activity Patterns of Mayfly Nymphs (Ephemeroptera)." *Canadian Journal of Zoology*, Vol. 155 (1968), pp. 201-221.
- Ellstrand, N.C., and Elam, D.R. "Population Genetic Consequences of Small Population Size: Implications for Plant Conservation." *Annual Review of Ecology and Systematics*, Vol. 24 (1993), pp. 217-242.
- Fahrig, L., and Merriam, G. "Conservation of Fragmented Populations." *Conservation Biology*, Vol. 8 (1994), pp. 50–59.
- Fahrig, L. and Paloheimo, J.E. "Determinants of local Population Size in Patchy Habitats. "*Theoretical Population Biology*, Vol. 34 (1988), pp. 194-213.
- Francis, C.D., Ortega, C.P., and Cruz, A. "Different Behavioral Responses to Anthropogenic Noise by Two Closely Related Passerine Birds." *Biology Letters*, Vol. 7 (2011), pp. 850-852.
- Gibbs, J.P. "Distribution of Woodland Amphibians Along a Forest Fragmentation Gradient."

Landscape Ecology, Vol. 13 (1998), pp. 263-268.
- Habib, L., Bain, E.M., and Boutin, S. "Chronic Industrial Noise Affects Pairing Success and Age Structure of Ovenbirds Seiurus aurocapilla." *Journal of Applied Ecology*, Vol. 44 (2007), pp. 176–184.
- Honnay, O., Jacquemyn, H., Bossuyt, B., and Hermy, M. "Forest Fragmentation Effects on Patch Occupancy and Population Viability of Herbaceous Plant Species." *The New Phytologist*, Vol. 166 (2005), pp .723-736.
- Karraker N., and Ruthig, G. "Effect of Road Deicing Salt on the Susceptibility of Amphibian Embryos to Infection by Water Molds." *Environmental Research*, Vol. 109 (2008), pp. 40-45.
- Kovats, Z.E., Ciborowski, J.J.H., Corkum, L.D. "Inland Dispersal of Adult Aquatic Insects." *Freshwater Biology*, Vol. 36 (1996), pp. 265–76.
- Lengagne, T. "Traffic Noise Affects Communication Behavior in a Breeding Anuran, Hyla arborea." *Biological Conservation*, Vol. 141 (2008), pp.2023-2031.
- Lohr, B., Wright, T.F., and Dooling, R.J. "Detection and Discrimination of Natural Calls in Masking Noise by Birds: Estimating the Active Space of a Signal." *Animal Behavior*, Vol. 65 (2003), pp. 763-777.
- Megahan, W.F. "Road Effects and Impacts - Watershed." In: *Proceedings of the Forest Transportation Symposium - Casper, Wyoming: December 11-13, 1984*. U.S. Department of Agriculture, Forest Service, Rocky Mountain Region, Engineering Staff Unit. p. 22.
- Nicieza, A.G., and Metcalfe, N.B. "Effects of Light Level and Growth History on Attack Distances of Visually Foraging Juvenile Salmon in Experimental Tanks." *Journal of Fish Biology*, Vol. 51 (1997), pp. 643–649.
- Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C. "The Natural Flow Regime: A Paradigm for River Conservation and Restoration." *Bioscience*, Vol. 47 (1997), pp. 769–784.
- Perkin, E.K., Hölker, F., Richardson, J.S., Sadler, J.P., Wolter, C., and Tockner, K. "The Influence of Artificial Light on Stream and Riparian Ecosystems: Questions, Challenges, and Perspectives. " *Ecosphere*, Vol. 2:art122.
- Poot, H., Ens, B.J., de Vries, H., Donners, M.A.H., Wernand, M.R., and Marquenie, J.M. "Green Light for Nocturnally Migrating Birds." *Ecology and Society*, Vol. 13 (2010), p. 47.
- Prasad, A., at al. (2010). Prasad, A., Iverson, L., Peters, M., Bossenbroek, J., Matthews, S., Davis Sydnor, T., and Schwartz, M. "Modeling the Invasive Emerald Ash Borer Risk of Spread Using a Spatially Explicit Cellular Model." *Landscape Ecology*, Vol. 25 (2006), pp. 353-369.
- Rich, C., and Longcore, T. *Ecological Consequences of Artificial Night Lighting* (Island Press, Washington, D.C.: 2006).
- Robinson, S.K., Thompson, F.R., Donovan, T.M., Whitehead, D.R., and Faaborg, J. "Regional Forest Fragmentation and the Nesting Success of Migratory Birds." *Science*, Vol. 267 (1995), pp. 1987-1990.
- Ryan, P.A. "Environmental Effects of Sediment on New Zealand Streams." *New Zealand Journal of Marine and Freshwater Research*, Vol 25 (1991), pp. 07-221.
- Schaub, A., Ostwald, J., and Siemers, B.M. "Foraging Bats Avoid Noise." *The Journal of Experimental Biology*, Vol 211 (2008), pp. 3174-3180.
- Trzcinski, M.K., Fahrig, L., and Merriam, G. "Independent Effects of Forest Cover and Fragmentation on the Distribution of Forest Breeding Birds." *Ecology Applications*, Vol. 9 (1999), pp. 586-593.
- U.S. Environmental Protection Agency. *Air Quality Criteria for Ozone and Related Photochemical Oxidants, 2006 Final*. EPA/600/R-05/004aF-cF (Washington, DC: 2006).

- U.S. Environmental Protection Agency. *Integrated Science Assessment (ISA) for Oxides of Nitrogen and Sulfur Ecological Criteria, Final Report.* EPA/600/R-08/082F (Washington, D.C, 2008).
- U.S. Environmental Protection Agency. (2010a.) U.S. Environmental Protection Agency. "Flow Alteration." In: Causal Analysis/Diagnosis Decision Information System (CADDIS), Accessed from http://www.epa.gov/caddis/ssr_flow_int.html, Last updated September 23, 2010.
- U.S. Environmental Protection Agency. (2010b). "Ionic Strength." In: Causal Analysis/Diagnosis Decision Information System (CADDIS), Accessed from http://www.epa.gov/caddis/ssr_ion_int.html, Last updated September 23, 2010.
- U.S. Environmental Protection Agency. (2010c). "Sediments." In: Causal Analysis/Diagnosis Decision Information System (CADDIS), Accessed from http://www.epa.gov/caddis/ssr_sed_int.html, Last updated September 23, 2010.
- Vosyliené, M.Z., Baltrénas, P., and Kazlauskiené, A. "Toxicity of Road Maintenance Salts to Rainbow Trout *Oncorhynchus mykiss." Ekologija,* Vol 2 (2006), pp. 15-20.
- Wise, S. "Studying the Ecological Impacts of Light Pollution on Wildlife: Amphibians as Models." *Journal of Thermal Biology* , Vol. 6, (2007), pp. 107-116.
- Wise, S.E., and Buchanan, B.W. "Influence of Artificial Illumination on the Nocturnal Behavior and Physiology of Salamanders." In: Rich, C., and Longcore, T., eds, *Ecological Consequences of Artificial Night Lighting (* Island Press: 2006), pp. 221-251.
- Ziegler, A.D., Sutherland, R.A., and Giambelluca, T.W. "Runoff Generation and Sediment Production on Unpaved Roads, Footpaths and Agricultural Land Surfaces in Northern Thailand." *Earth Surface Processes and Landforms*, Vol. 25 (2000), pp. 519-534.

Chapter 8: Induced Seismicity

- De Pater and Baisch. (2011). de Pater, C.J. and Baisch, S. "Geomechanical Study of Bowland Shale Seismicity." *Synthesis Report* (Bucknell University, Lewisberg, Pennsylvania: November 2011).
- Evans, D. M. "Man-Made Quakes in Denver." *Geotimes,* Vol. 10 (1966), pp. 11-17.
- Ellsworth, W., S. Hickman, E. Llenos, A. McGarr, A. Michael and J. Rubinstein. "Are Seismicity Rate Changes in the Midcontinent Natural or Manmade?" *Seismological Research Letters*, Vol. 83, No. 2 (2012).
- Fletcher, J.B. and L.R. Sykes. "Earthquakes Related to Hydraulic Mining and Natural Seismic Activity in Western New York State." *Journal of Geophysical Research*, Vol. 82, No. 26 (1977), pp. 3767-3780.
- Frohlich, C. E., Potter, Hayward C., and Stump, B. "Dallas-Fort Worth Earthquakes Coincident With Activity Associated with Natural Gas Production." *Leading Edge,* Vol. 29, No. 3 (2010), pp. 270-275.
- Healy, J.H, Rubey, W.W., Griggs, D.T., and Raleigh, C.B. "The Denver Earthquakes." *Science,* Vol.161 (1968), pp.1301-1310.
- Hsieh, P. and Bredehoft, J. "Reservoir Analysis in the Denver Earthquakes: A Case of Induced Seismicity." *Journal of Geophysical Research*, Vol. 86: B2 (1981), pp. 903-920.
- Herrman, R.B., Park, S.K., and Wang, C.Y. "The Denver Earthquakes of 1967-1968," *Bulletin of the Seismological Society of America,* Vol. 71 (1981), pp. 731-745.
- Holland, A. *Examination of Possibly Induced Seismicity from Hydraulic Fracturing in the Eola Field, Garvin County, Oklahoma*. Oklahoma Geological Survey, Open-File Report, OF1-2011, Sarkeys Energy Center (Norman, Oklahoma: August 2011).

- Luza, K.V. and Lawson, J.E., Jr. "Seismicity and Tectonic Relationships of the Nemaha Uplift." In: Oklahoma, *Part 3: Oklahoma Geological Survey Open-file Report.* NUREG/CR-1500, (prepared for the U.S. Nuclear Regulatory Commission: 1980).
- McDonald, A.J. MSc Thesis (University of Witwatersrand, Johannesburg: 1982).
- McGarr, A., Sompson, D., and Seeber, L. "Case Histories of Induced and Triggered Seismicity." In: *International Handbook of Earthquake and Engineering Seismology, Part 2* (2003*)*, pp. 647-661.
- National Research Council. *Induced Seismicity Potential in Energy Technologies.* No. 13355, (National Academies Press: Washington, DC: 2012).
- Raleigh C.B., Healy J.H., and Bredehoeft, J.D. "An Experiment in Earthquake Control at Rangeley, Colorado." *Science*, Vol. 191 (1976), pp. 1230-1237.

Appendix B: Glossary of Terms

- The Encyclopedia of Earth. "Ecology Theory: Indicator Species." Accessed August 24, 2012 from http://www.fws.gov/midwest/endangered/glossary/index.html.
- "Schlumberger - The Oilfield Glossary." Accessed August 24, 2012 from http://www.glossary.oilfield.slb.com/default.cfm.
- U.S. Department of Energy. *Modern Shale Gas Development in the United States: A Primer*. Office of Fossil Energy, National Energy Technology Laboratory, April 2009.
- U.S. Environmental Protection Agency. "Greening EPA Glossary." Accessed August 24, 2012 from http://www.epa.gov/oaintrnt/glossary.htm#v.
- U.S. Environmental Protection Agency. "Private Wells Glossary." Accessed August 24, 2012 from http://water.epa.gov/drink/info/well/glossary.cfm
- http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/wells_hydrowhat.cfm.
- U. S. Fish and Wildlife Service. "Endangered Species Glossary." Accessed August 24, 2012 from http://www.fws.gov/midwest/endangered/glossary/index.html.